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V.1, PT.1

Space Station Freedom External Maintenance Task Team

Final Report

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July 1990

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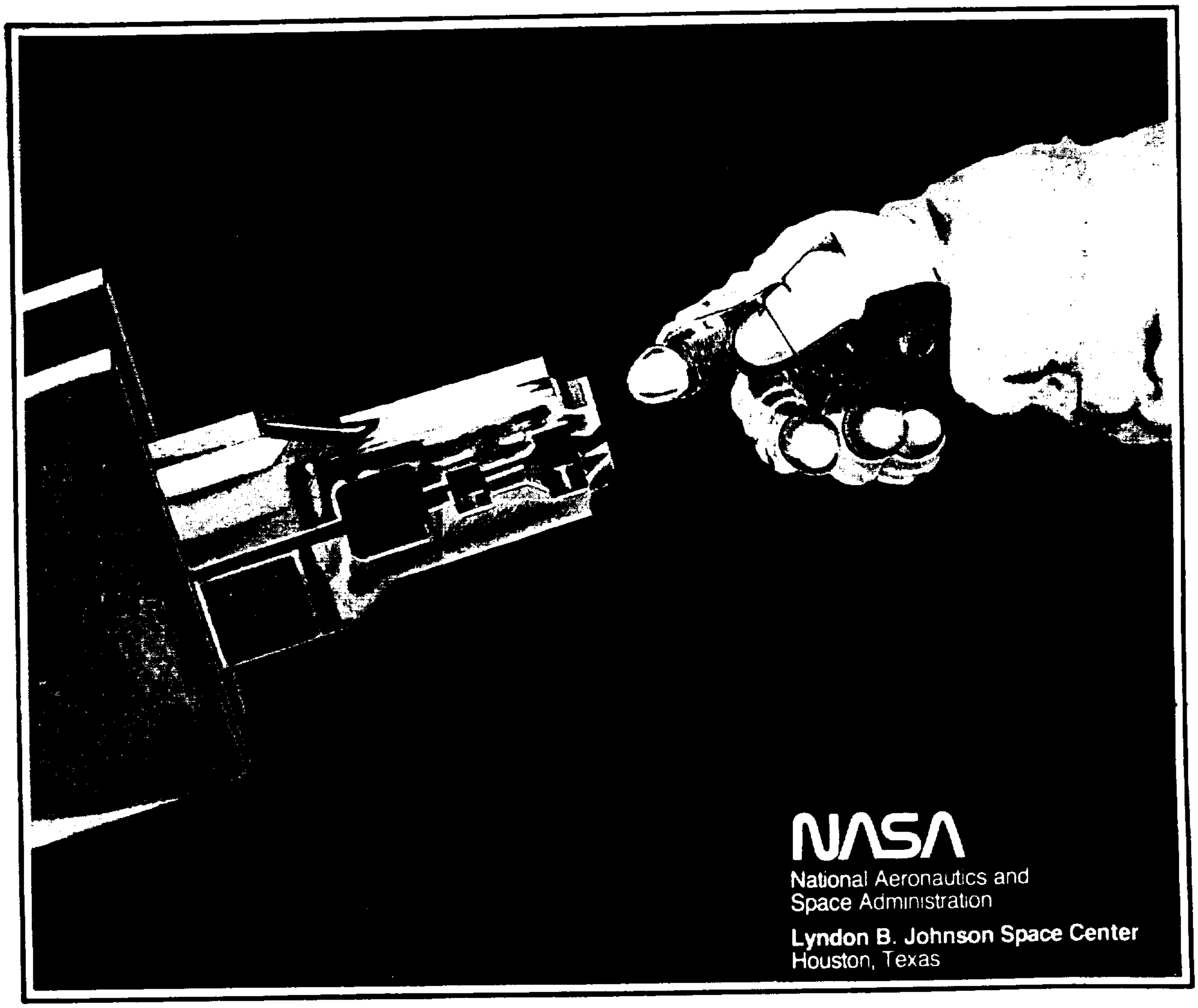

Volume I, Part 1

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External Maintenance Task Team

Final Report

July 1990

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Appendix I Space Station Freedom Reconfiguration Options

Acronyms and Abbreviations

AC	Assembly Complete
AL	Air Lock
AOA	Assembly Operation Assessment
APS	Astronaut Positioning System
ASPS	Attachment Stabilization and Positioning System
BIT	Built-in Test
CCTV	Closed Circuit Television
CDR	Critical Design Review
CEI	Contract End Item
CETA	Crew and Equipment Translation Aid
CG	Center of Gravity
CIL	Critical Items List
CM	Center of Mass
CMG	Control Moment Gyro
COTS	Commercial Off-the-Shelf
CPU	Central Processing Unit
CSA	Canadian Space Agency
D&C	Display and Controls
DCD	Design Criteria Document
DM	Dexterous Manipulator
DMS	Data Management System
DOF	Degree of Freedom
DTC	Design-to-Cost
DTF	Development/Demonstration Test Flight
EE	End Effector
EMTT	External Maintenance Task Team
EMU	Extravehicular Mobility Unit
EVA	Extravehicular Activity
EVAS	EVA System
EVR	Extra Vehicular Robotic
EV	Extravehicular
FEL	First Element Launch
FMEA	Failure Modes and Effects Analysis
FP	Fisher-Price
FTS	Flight Telerobotic Servicer

g	Gravity
GE	General Electric
GFE	Government Furnished Equipment
GPC	General Purpose Computer
GSFC	Goddard Space Flight Center
HST	Hubble Space Telescope
ICD	Interface Control Document
IEA	Integrated Equipment Assembly
IP	International Partner
IR	Infrared
ITA	Integrated Test Area
IVA	Intravehicular Activity
JEM	Japanese Experiment Module
JPL	Jet Propulsion Laboratory
JSC	Lyndon B. Johnson Space Center
KSC	John F. Kennedy Space Center
LCC	Life Cycle Cost
LDEF	Long Duration Exposure Facility
LEE	Latching End Effector
LeRC	Lewis Research Center
MAGIK	Manipulator Analysis - Graphic, Interactive, Kinematic
MBS	MRS Base System
MDSSC-SSD	McDonnell Douglas Space Systems Company - Space Station Division
MIL-STD	Military Standard
MLI	Multilayer Insulation
MMD	Micrometeroid Debris
MPAC	Multipurpose Application Console
MPTT	Multipurpose Torque Tool
MRS	Mobile Remote Servicer
MSC	Mobile Servicing Center
MSIS	Robotic Systems Integration Standard
MSS	Mobile Servicing System
MT	Mobile Transporter
MTBF	Mean Time Between Failure
MTBMA	Mean Time Between Maintenance Actions
MTBP	Mean Time Between Penetration
MTTR	Mean Time to Replace
ORU	Orbital Replacement
OSE	Ocean Systems Engineering, Inc.
PDGF	Power Data Grapple Fixture
PDR	Preliminary Design Review

PDP	Programmable Display Pushbutton
PERT/CPM	Program Evaluation Review Technique/Critical Path Method
PFR	Portable Foot Restraint
PNP	Probability of No Penetration
POR	Point of Resolution
PRACA	Problem Reporting and Corrective Action
PRLA	Payload Retention Latch Assembly
PWP	Portable Work Platform
PWS	Portable Workstation
QD	Quick Disconnect
RADC	Rome Air Development Center
RMS	Remote Manipulator System
RPS	RMS Planning System
RSEL	Robotic Systems Evaluation Laboratory
RSIS	Robotic Systems Integration Standard
RTAIL	OSE's Robotics Testing and Integration Laboratory
SAE	Storage Accommodation Equipment
SAIC	Science Applications International Corp.
SPAR	SPAR Aerospace Ltd.
SPDM	Special Purpose Dexterous Manipulator
SRMS	Shuttle Remote Manipulator System
SSF	Space Station Freedom
SSRMS	Space Station Remote Manipulator System
STD	Standard
TBD	To Be Determined
TR	Telerobot
ULC	Unpressurized Logistics Carrier
UPT	User-Provided Tool
WAF	Work Site Attachment Fitting
WETF	Weightless Environmental Test Facility
WP	Work Package

ORU Count

Appendix B

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ORU Count

Abstract

This appendix presents a proposed solution to the confusion regarding the designation of devices as ORUs and the subsequent accounting for external maintenance actions. It is recommended the PDRD (SSP 30000) requirements be changed to allow designers to select those items which will be counted as ORUs. This selection should yield the optimum complement of ORUs that will support requirements such as safety, logistics, and reliability. In parallel with this, a method is proposed to account for those devices, other than ORUs, which are changed out on orbit, and, to account for non-changeout maintenance actions.

Introduction

While the SSP 30000 definition of an ORU is reasonably clear, interpretation of lower-level requirements (e.g., JSC 31000) has caused some maintenance actions not to be counted. The EMTT has accounted for approximately 6,000 ORUs at Assembly Complete; however, there appear to be maintenance actions other than ORU changeout which will require EVA or robotic resources.

Statement of Problem

The term ORU is a maintenance term used to describe maintenance practices only. This term should not be used to describe logical hardware breakdowns or indenture levels. By defining an ORU as the *lowest* level which *can be* replaced, SSP 30000 has introduced a question of judgment regarding the possibility of changing out a specific device rather than the desirability of selecting that device for changeout. Furthermore, specific requirements have been developed by the work packages (e.g., JSC 31000) that impose stringent requirements on the design of any device designated an ORU. These include requirements such as automated fault detection and direct access to all ORUs. In some cases, it may not be feasible or possible for a device (e.g., a truss strut member) to meet all current ORU design requirements. Under the current criteria, these devices would not be counted as ORUs and would, therefore, not be included in maintenance requirements based on ORU changeout.

In addition, it is anticipated that some maintenance actions will be required which do not involve ORU changeout. These would include inspection tasks, some preventive maintenance tasks (e.g., star tracker realignment), and in-situ repair. To fully account for all maintenance requirements, these tasks must be included.

Approach

An ORU selection process must be developed which is based on cognizance of logical hardware indenture levels, operational mission constraints, and life cycle costs. This "lowest level" selection of ORUs is not necessarily the absolute lowest level that can possibly be attained. Rather, this selection is based on a quantitative assessment of options driven by the impact of that selection on crew maintenance requirements, logistics load, maintainability, etc. Under this process, the selection of ORUs should take place prior to the application of ORU design requirements. As the design becomes better defined, the selection of ORUs is iterated with the objective of verifying that the level chosen is the most appropriate, considering these factors.

Following selection, an assessment is made of the practicality of applying all ORU design criteria to the selection. Should this be impractical, waivers of those design requirements will be sought. The alternative to the submission of waivers would be the development of a classification scheme which would establish ORU categories, each of which would have different design requirements. For example:

- Class 1 ORU - meets all current requirements for fault detection, accessibility, etc.
- Class 2 ORU - meets all requirements except fault detection
- Class 3 ORU - meets all requirements except accessibility

The risk with an approach of this type is the tendency to use such a system to push "block waivers" through the program. We can also be assured that regardless of the classification system proposed today, it will need to be modified in the future to cover new requirements or omissions. The advantage of a classification approach is that it avoids the waiver process. This, however, is actually a false savings because the amount of analysis that goes into processing a waiver is fundamentally the same as that required to properly categorize ORUs in a classification system.

Results and Discussion

1. SSP 30000, Sect. 3, Part 1, defines an ORU as "The *lowest* level of component or subsystem hardware that *can be* removed and replaced on location under orbital conditions."
2. JSC 31000, Rev. 3, places some 36 additional requirements on ORUs that specify such things as servicing agent, fault detection and isolation, accessibility, and some system-specific requirements.
3. Considering ORU removal and replacement does not account for *all* maintenance actions required on board SSF.
4. There is some confusion between maintenance, servicing, and operations.

It is clear that the objective of the External Maintenance Task Team (EMTT) is to account for all external maintenance requirements rather than to account for all external ORUs. In addition to to ORU changeout, the following maintenance tasks are assumed to exist:

- Preventive maintenance
- Inspection
- In-situ repair of equipment that involves other than remove and replace actions

Although it is believed the EMTT has received all of the data which are available to date, future allocations will depend on knowledge of all maintenance requirements and not just ORU exchanges.

Furthermore, our operations experience leads us to believe repair actions will be attempted at levels below the ORU level. For example, the APAE will have a latch system which attaches the deck carrier to the SIA. While it has not been determined where the active part of this system (motors, switches, linkages, hooks, etc.) will be located, no part of this subsystem is presently considered an ORU. A failure of the latch mechanism will require either the deck carrier (with its attached payloads) be returned for latch mechanism repair or that the SIA (and the deck carrier if no on-orbit stowage location is available) be returned for repair. Our experience leads us to conclude that either the program will ferret out systems like this and attempt to convert them to ORUs (as with the HST block 2 ORUs) or work-around tasks will be developed to correct the failure.

The fundamental question here is that of defining ORUs at the appropriate level based on factors such as logical hardware indenture levels, operational mission constraints, and life cycle cost. It is naive to believe we can make that decision today. Rather, we will continue as in past programs, to view this selection process as iterative. Today's ORUs may be deselected, and non-ORU or new systems may be selected. Although today's emphasis (i.e., the EMTT charter) is on reliability and maintainability, tomorrow's primary focus may shift to logistics (resupply, inventory, etc.). In that case, we may change our ORU selection level (e.g., boards versus boxes) based on considerations we are ignoring today.

This raises the issue of the SSP 30000 definition. The questions is, should the requirement read, "...that *can be* removed and replaced...", or, "...that *is selected to be* removed and replaced..."? The unanimous feeling of the developers present (WP-2, WP-3, WP-4, and CSA) was that the definition should be changed. This would eliminate some of the existing confusion and conflict by removing the judgment associated with"can be" and making this a design decision. That sounds illogical, but, think about it for a while.

Recommendations

The EMTT recommends a change in the definition of an ORU to allow the design to select the ORU level based on the factors discussed above. In addition, the question of what maintenance actions have been omitted must be addressed. The questions basically are (1) Do such actions exist? (2) What reporting mechanisms exist for tracking these actions? (3) Are those reporting mechanisms consistent across the program? and (4) What changes should be made to the documentation to ensure all maintenance actions are captured by the activities which succeed the EMTT?

Although the subject of ORU classification and a hierarchy of maintainability design requirements might be appropriate for further study, the EMTT does not support a classification approach at this time and recommends the continued use of a waiver process for ORU design criteria.

Acknowledgments

This appendix was developed in cooperation with the McDonnell Douglas Space Systems Company-Space Station Division (MDSSC-SSD). The principal author is Rick Newcomb, Staff Manager, Maintainability Integration and Analysis, MDSSC-SSD.

Bibliography

SSP 30000, Sect. 3

JSC 31000, Rev E

ORU Worksite Replacement Times

Appendix C

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ORU Worksite Replacement Times

As indicated in Volume I, Part 1, the ORU worksite replacement times are based solely on NASA, contractor and international partner estimates. The EMTT attempted to make an independnent evaluation of these times, but found ORU designs too immature for adequate analysis.

As ORU designs are developed, an independent evaluation of all the replacement times will be necessary.

ORU Worksite

Replacement Times

ORU WORKSITE TIME

WP-1

ORU NAME	QUAN	MTTR
Multi Layer Insulation (Longerons & Aft Trunions)	12	5.06
Interface Manifold	4	2.33
Interface Assembly	8	2.33
Interface Manifold	2	2.33
Multi Layer Insulation (Forward Trunions & Keel Pins)	18	1.60
Power Cables	16	1.43
Electrical Junction Box	4	1.38
Window/Trapezoidal	12	0.83
Window/Round	5	0.83
Vent Valve (PMMS)	1	0.75
Vent & Relief Isolation Valve	10	0.75
Shut-Off Valves	30	0.75
PRTC Valves	6	0.75
Valve with Heater	2	0.75
Valve Without Heater	3	0.75
Meteorite Debris Shield	246	0.66
Window Shutters/Trapezoidal	12	0.58
Window Shutter/Round	5	0.33
	AVERAGE WORKSITE TIME	1.34

ORU WORKSITE TIME

WP-2

ORU NAME	QUAN	MTTR
Control Moment Gyro Assembly (CMG)	6	4.00
Thermal Radiator Rotary Joint Bearing Assembly	2	3.00
Solar Alpha Rotary Joint Assembly	2	3.00
Heat Exchanger Units	18	2.17
TDRSS Parabolic Antenna	2	2.00
Line Heater Strip	2	2.00
Truss Node Assembly	128	2.00
External Module Coldplates	8	2.00
Umbilical Service Set Node 4	1	1.50
Umbilical Service Set Node 3	1	1.50
Umbilical Service Set Node 2	1	1.50
Umbilical Service Set Node 1	1	1.50
Space to Space Parabolic Antenna Assembly	4	1.50
Recirculating Control Valve	8	1.50
Pumping Module	8	1.50
Umbilical Assembly	2	1.50
Cable Assembly SPDA to MDM	1	1.50
Cable Assembly SPDA to Motor Control	1	1.50
Cable Assembly SPDA to PDGF	1	1.50
Harness Assembly Fiber Optic	8	1.50
Harness Assembly COAX	10	1.50
Harness Assembly Payload/Subsystem	2	1.50
Harness Assembly SPDA to MRS Simulator	2	1.50
Harness Assembly SPDA to C & T	10	1.50
Harness Assembly SPDA to Payload	2	1.50
Harness/Umbilical Assembly Power ORU to SPDA	4	1.50
Harness/Diode/Umbilical Assembly 150UDC	4	1.50
Location/Position Monitoring Device	2	1.50
Lower Base	1	1.50

ORU WORKSITE TIME

WP-2

ORU NAME	QUAN	MTTR
Track Base Assembly	1	1.50
Turntable Assembly	1	1.50
Tubing & Fitting Set	26	1.50
Power Cable Starboard Transverse Boom Tr 2	1	1.50
Power Cable Port Transverse Boom Tr 2	1	1.50
Power Cable Starboard Transverse Boom Tr 1	1	1.50
Power Cable Port Transverse Boom Tr 1	1	1.50
Starboard Propulsion Module Cable Assembly	1	1.50
Port Propulsion Module Cable Assembly-Power	1	1.50
Node 3 & 4 Umbilical Cable Assembly	1	1.50
Node 2 Umbilical Cable Assembly - Power	1	1.50
Node 1 Umbilical Cable Assembly - Power	1	1.50
Pallet Power Cable Assembly - 021	4	1.50
Pallet Power Cable Assembly - 017	21	1.50
Pallet Power Cable Assembly - 015	44	1.50
Pallet Power Cable Assembly - 013	7	1.50
Pallet Power Cable Assembly - 011	4	1.50
Pallet Power Cable Assembly - 009	2	1.50
Pallet Power Cable Assembly - 007	28	1.50
Pallet Power Cable Assembly - 005	1	1.50
Pallet Power Cable Assembly - 003	41	1.50
Interface Power Cable Assembly - 017	12	1.50
Interface Power Cable Assembly - 015	24	1.50
Interface Power Cable Assembly - 013	11	1.50
Interface Power Cable Assembly - 011	4	1.50
Interface Power Cable Assembly - 009	6	1.50
Interface Power Cable Assembly - 007	3	1.50
Interface Power Cable Assembly - 005	10	1.50
Starboard C & T Cable Assembly - Power	1	1.50

ORU WORKSITE TIME

WP-2

ORU NAME	QUAN	MTTR
Port C & T Cable Assembly - Power	1	1.50
Load Converter	4	1.50
Electrical Harness (Pallet)	3	1.50
Slide Mechanisms	3	1.00
Inertial Sensor Assembly	3	1.00
Star Tracker	3	1.00
GPS Low Noise Amplifier	3	1.00
Ku-Band TDRSS Antenna Controller	4	1.00
Ku-Band TDRSS Transmit-Receiver	4	1.00
Space to Space Subsystem Parabolic Antenna Controller	4	1.00
Assembly & Contingency Transmit-Receive Amplifier	2	1.00
Space to Space Subsystem Transmitter - Receiver Type 2	4	1.00
Space to Space Subsystem Transmitter - Receiver Type 3	6	1.00
UHF Omni Antenna	4	1.00
Supply Tank	1	1.00
Pressure Regulator Ammonia	8	1.00
Module Support Structure	24	1.00
Condenser/Subcooler Module	28	1.00
Multiplexer/Demultiplexer SC	15	1.00
Multiplexer/Demultiplexer-MS	35	1.00
CETA Platform	1	1.00
Drive Module, Linear Joint	4	1.00
Drive Module, Wrist Joint	4	1.00
Drive Module, Elbow Joint	4	1.00
Drive Module, Shoulder Joint	4	1.00
Deployment Assembly, Shoulder	4	1.00
Umbilical Mechanism Harness	2	1.00
Connector Assembly	2	1.00
Drive Assembly	2	1.00

ORU WORKSITE TIME

WP-2

ORU NAME	QUAN	MTTR
Connector Mechanism Assembly	1	1.00
Motor Drive Electronics	2	1.00
Harness Assembly, Upper	1	1.00
Harness Assembly, Lower	1	1.00
Drive Hinge Assembly	1	1.00
Propulsion Wire Harness	8	1.00
Berthing Latch Assembly	24	1.00
Mixed Waste Gas Discharge Filter Assembly	1	1.00
N2 SC Heater Assembly	2	1.00
Logistics Carrier Wire Harness	10	1.00
Berthing Latch Assembly	30	1.00
Locking Mechanism	2	1.00
Radiator Boom Assembly	2	1.00
Instrumentation Package	2	1.00
Drive Assembly	4	1.00
Locking Mechanism	2	1.00
Instrumentation Package	2	1.00
Power/Data Transfer Module (PDTM)	2	1.00
Drive Assembly	4	1.00
Bearing Assembly	2	1.00
Alpha/Radiator Joint Electronics	8	1.00
EVA Translation System Rail & Supports	1	1.00
Ring Concentrator (RC)	10	1.00
MDM-SC (Pallet 5)	2	1.00
Interconnect Valve Assembly	1	1.00
Heat Exchanger Node 4	1	1.00
Heat Exchanger Node 3	1	1.00
Heat Exchanger Node 2	1	1.00
Heat Exchanger Node 1	1	1.00

ORU WORKSITE TIME

WP-2

ORU NAME	QUAN	MTTR
Harness Assembly, Wrist Joint	4	1.00
Harness Assembly, Wrist Boom	4	1.00
Harness Assembly, Up Radial Joint	4	1.00
Harness Assembly, Shoulder Joint	4	1.00
Harness Assembly, Shoulder Boom	4	1.00
Harness Assembly, Low. Radial Boom	4	1.00
Harness Assembly, Linear Boom Deployment	4	1.00
Harness Assembly, Linear Boom	4	1.00
Harness Assembly, Elbow Joint	4	1.00
Drive Module, Linear Boom Deployment Joint	4	1.00
Drive Electronics	2	1.00
CMG Electronics Assembly (EA)	12	1.00
Harness Assembly, Shoulder Deployment	4	1.00
MSC Guide Pins	80	0.80
EV Umbilical Stowage System	1	0.75
Portable Work Platform Stowage	2	0.75
ESET Stowage	2	0.75
Portable Decontamination Station Structure	2	0.75
CMDM Control Electronics	2	0.75
Portable EVA Luminaire	2	0.50
External Video Switch	2	0.50
External TV Camera Assembly	8	0.50
Pressure Regulator (N2)	9	0.50
Isolation Valve	12	0.50
Accumulator	4	0.50
Radiator Panel	80	0.50
Clothesline Assembly	2	0.50
Portable Foot Restraint Socket	10	0.50
Portable Foot Restraint Workstation Stantion	2	0.50

ORU WORKSITE TIME

WP-2

ORU NAME	QUAN	MTTR
Safety Tether Reels	2	0.50
Handholds	10	0.50
Handrails	21	0.50
Contamination Removal Unit	2	0.50
Portable Work Platform	2	0.50
Airlock External Cables	1	0.50
Depress Display & Control Panel (External)	1	0.50
Seal Set	1	0.50
Latching Mechanism Assembly	1	0.50
Actuation Mechanism Assembly	1	0.50
Crewlock Hatch Assembly	1	0.50
Resistojet Module	4	0.50
Upper Base Latch Assembly	4	0.50
Upper Base	1	0.50
Lower Base Latch Motor Assembly	4	0.50
Umbilical/Drive Motor Assembly	2	0.50
Fluid Control Cable Assembly	20	0.50
Umbilical Flex Hose	24	0.50
Harness 1553 Bus Propulsion Berth	16	0.50
N2 Pressure Sensor Assembly	2	0.50
N2 Vent/Safety Assembly	2	0.50
Harness 1553 Bus Logistics Carrier Berth	20	0.50
Logistics Carrier Latch Umbilical Control	10	0.50
Docking Target Luminaire	2	0.50
Video Camera Luminaire	11	0.50
EVA Luminaire	32	0.50
Tracking/Anti-Collision Luminaire	2	0.50
Free Flyer Luminaire	2	0.50
Orientation Luminaire	7	0.50

ORU WORKSITE TIME

WP-2

ORU NAME	QUAN	MTTR
Stb'd. TCS Radiator Pallet Insulation	1	0.50
Stb'd. TCS Radiator Pallet Micro-Meteorite Protection	1	0.50
Port TCS Radiator Pallet Insulation	1	0.50
Port TCS Radiator Pallet Micro-Meteorite Protection	1	0.50
G N & C Pallet Insulation Set	1	0.50
G N & C Pallet Micro-Meteorite Protection	1	0.50
FMAD Pallet Insulation Set	1	0.50
FMAD Pallet Micro-Meteorite Protection	1	0.50
IUDP Pallet Insulation Set	2	0.50
IUDP Pallet Micro-Meteorite Protection	2	0.50
MSC Umbilical Supports	6	0.50
Deployable Utility Tray Covers	742	0.50
Deployable Utility Tray Barrier	915	0.50
Diagonal Strut Assembly	148	0.50
Longeron Strut Assembly	244	0.50
Reducing Waste Gas Vent/Safety Assembly	1	0.40
Instrumentation Assembly	2	0.40
Thermal Insulation Strip	1	0.29
Portable Foot Restraints (PFR)	2	0.25
Portable Contamination Detector	2	0.25
Hatch Window Assembly	1	0.25
Umbilical Mechanism	8	0.25
Umbilical Mechanism	10	0.25
Reducing Waste Gas Compressor Asembly	2	0.18
Mixed Waste Gas Dryer Assembly	2	0.09
Reducing Waste Gas Internal Pressure Sensor Assembly	2	0.06
Mixed Waste Gas Compressor Assembly	2	0.04
Reducing Waste Gas Dryer Assembly	2	0.04
Tank Inlet Control Assembly	2	0.04

ORU WORKSITE TIME

WP-2

ORU NAME	QUAN	MTTR
Tank Discharge Control Assembly	2	0.04
Pressure Bleed Assembly	1	0.03
Mixed Waste Gas Internal Pressure Sensor Assembly	2	0.02
Mixed Waste Gas Vent/Safety Assembly	1	0.02
Mixed Waste Gas Inlet Pressure Sensor Assembly	1	0.02
Reducing Waste Gas Discharge Filter Assembly	1	0.02
Reducing Waste Gas Inlet Pressure Sensor Assembly	1	0.02
Waste Gas Dump Assembly	1	0.02

AVERAGE WORKSITE TIME 0.96

ORU WORKSITE TIME

WP-3

ORU NAME	QUAN	MTTR
Worksite Attachment Fixture (WAF)	1	0.00
Multiple Payload Adapter (MPA)/Payload	1	0.00
Payload Interface Adapter	20	0.00
-X ORU	2	0.00
+X Oru	1	0.00
Station Interface Adapter (SIA)	1	0.00
	AVERAGE WORKSITE TIME	0.00

ORU WORKSITE TIME

WP-4

ORU NAME	QUAN	MTTR
Photo-Voltaic Cable Set	4	12.00
Integrated Equipment Assembly Transition Structure	4	6.00
Power Management And Distribution Cable Set	1	3.06
Photo-Voltaic Utility Plate Type 2	24	2.50
Integrated Equipment Assembly	4	2.00
Deployable Mast & Canister	8	2.00
Beta Gimbal Assembly	8	2.00
Beta Gimbal Bearing Subassembly	8	1.50
Electrical Junction Box	8	1.36
Fluid Junction Box	8	1.23
Radiator Subassembly	4	1.00
Photo-Voltaic Utility Plate Type 1	8	1.00
Photo-Voltaic Blanket & Box (L & R)	16	1.00
Sequential Shunt Unit	8	0.58
Pump	8	0.58
Photo-Voltaic Control Unit (PVCU)	8	0.58
Main Bus Switching Unit Integrated Truss Assembly	4	0.58
DC to DC Converter Unit - IEA	4	0.58
DC to DC Converter Unit (12.5 Kw)	32	0.58
DC Switch Unit	8	0.58
Beta Gimbal Drive Motor Assembly	8	0.50
Beta Gimbal Electronics Control Unit	8	0.33
Beta Gimbal Transition Structure	8	0.28
Beta Gimbal Roll Ring Assembly	8	0.25
Battery Subassembly	48	0.24
Battery Charge Discharge Unit (BCDU)	24	0.24
Remote Power Controller Type 4 (130 A) Telerobotic	37	0.20
Remote Power Controller Type 3 (50 A) Telerobotic	29	0.20
Remote Power Controller Type 2 (25 A) Telerobotic	9	0.20

ORU WORKSITE TIME

WP-4

ORU NAME	QUAN	MTTR
Remote Power Controller Type 1 (10 A) Telerobotic	75	0.20
	AVERAGE WORKSITE TIME	1.45

ORU WORKSITE TIME

CSA

ORU NAME	QUAN	MTTR
MRS Maintenance Depot Cable Harness	2	2.98
Joint Electronics Unit (JEU)	14	2.68
Electronic Module Cable Harness	22	2.52
Latching End Effector	1	2.50
Electronic Module Cable Harness	22	2.50
MRS System Cable Harness	1	2.48
Payload/ORU Accommodation Unit	2	2.20
Joint Drive Module	7	2.20
Joint Drive Module	5	2.20
Video Bus Interface Unit (VBIU)	4	2.04
CCTV Cameras and Lights	2	2.04
Arm Control Unit (ACU)	2	2.04
CCTV Cameras and Lights	2	2.00
CCTV Camera, Light, Pan & Tilt Unit Assembly	2	2.00
CCTV Camera, Light, Pan & Tilt Unit Assembly	2	2.00
Type 2 SSRMS Cable Harness	2	1.91
Type 1 SSRMS Cable Harness	2	1.91
Boom Thermal Blankets	4	1.72
SPDM Lower Body Segment	1	1.70
Joint Electronics Unit (JEU)	10	1.68
Power Data Grapple Fixture	6	1.54
Wiring Harness - Body	2	1.50
Roll/Yaw Joint Housing	4	1.34
Pitch Joint Housing	3	1.30
MRS Maintenance Depot Structure	1	1.20
MRS Base System Structure	1	1.20
Roll/Yaw Joint Housing	2	1.20
Roll Joint Housing (Neck)	1	1.20
Pitch Joint Housing	2	1.20

ORU WORKSITE TIME

CSA

ORU NAME	QUAN	MTTR
SPDM Upper Body Segment	1	1.00
Boom Sections	4	1.00
Artificial Vision Unit (AVU)	1	1.00
Video Distribution Unit (VDU)	2	0.90
Radio Frequency Unit	2	0.90
MRS Maintenance Depot PMDS/DMS Electronic Unit	2	0.75
Tool Rack	1	0.75
OMNI- Directional Antenna	8	0.75
Power Data Grapple Fixture	1	0.72
Pitch Joint Housing Thermal Blanket	3	0.64
Dexterous Arm	2	0.62
MRS Maintenance Depot Thermal Blankets	10	0.60
SPDM Upper Body Segment Thermal Blanket	1	0.60
Video Distribution Unit (VDU)	2	0.54
Tool Changeout Mechanism (TCM)	2	0.54
Main Body CCTV, Light & PTU	1	0.54
Latching End Effector (LEE)	2	0.54
Arm CCTV Camera	2	0.54
SPDM Lower Body Segment Thermal Blanket	1	0.50
Roll Joint Housing (Neck) Thermal Blanket	2	0.50
Pitch Joint Housing (B & U) Thermal Blanket	2	0.50
Roll/Yaw Joint Housing Thermal Blanket	2	0.50
Roll/Yaw Joint Housing Thermal Blanket	4	0.50
MRS Base System Thermal Blanket	8	0.50
Latching End Effector - Base	1	0.45
SPDM Main Control Computer (MCC)	2	0.44
Tools	1	0.40
Tools	1	0.40
Joint Control Processor (JCP)	2	0.40

ORU WORKSITE TIME

CSA

ORU NAME	QUAN	MTTR
AVERAGE WORKSITE TIME		1.26

ORU WORKSITE TIME

FTS

ORU NAME	QUAN	MTTR
Telerobot (TR) Computer	2	0.81
Storage Unit Controller	2	0.81
FTS Mass Storage Unit	1	0.81
Power Module	1	0.77
Regulator Charger Module	1	0.70
TR Redundant Controller	1	0.67
Communications Subsystem Module	1	0.67
Holster/Camera Control Electronics	1	0.66
Battery (20Ah)	3	0.64
Camera Positioning Assembly (CPA)	1	0.62
CPA Camera	2	0.62
Thermal Coatings - Clean	1	0.58
Camera Lamps	8	0.58
Radiator Panel Tool Holster	1	0.58
Node Attachment Tool (NAT)	1	0.58
Radiator Panel Tool (RPT)	1	0.58
Module Service Tool (MST)	1	0.58
FTS Umbilical Storage Holster	1	0.58
Antenna Assembly	2	0.58
Workstation Control Computer	2	0.58
Rotary Jaw Tool Holster	2	0.58
Parallel Jaw Tool Holster	2	0.58
End-Effector Changeout Mechanism (EECM) Holster	2	0.58
Manipulator	2	0.57
Crew Warning Device	4	0.57
Stabilizer Attachment, Stabilization & Positioning Subsystem	1	0.57
Double V-block Tool	2	0.52
Worksite Attach Mechanism (WAM)	1	0.52
EECM Removable Half	2	0.52

ORU WORKSITE TIME

FTS

ORU NAME	QUAN	MTTR
7/16 inch socket	1	0.52
1/2 inch Key Wrench	1	0.52
Wrist Camera Assembly	2	0.50
Contamination Sensor	4	0.49
Power Data Grapple Fixture (PDGF)	1	0.45
Worksite Attachment Fixture (WAF)	1	0.45
FTS Umbilical	1	0.25
	AVERAGE WORKSITE TIME	0.59

ORU WORKSITE TIME

ESA

ORU NAME	QUAN	MTTR
Airlock Outer Hatch	1	3.50
Viewport - Dark Cover	2	3.00
Airlock Outer Hatch Seal	1	2.50
Meteoroid Debris Protection System (MDPS) End Cone Sections	4	2.00
Meteoroid Debris Protection System (MDPS)Cylindrical Section	16	2.00
CO2 Tank(s)	4	0.00
A.O.H. Latching Mechanism	1	0.00
MPDS End Cone Section(s)	4	0.00
	AVERAGE WORKSITE TIME	1.63

ORU WORKSITE TIME

NASDA

ORU NAME	QUAN	MTTR
Seal Airlock Outer Hatch	1	2.60
Video Switcher (VSW)	4	2.50
Thermal Valve Controller (TVC)	4	2.50
Signal Processing Converter (SPC)	4	2.50
EF Power Switching Unit (EF-PSU)	4	2.50
Freon Pump Package (FPP)	2	2.50
Freon Accumulator Unit (FAU)	2	2.50
EF Heat Exchanger (EHX)	2	2.50
EF System Controller (ESC)	4	2.50
Berthing Mechanism Controller (BMC)	1	2.50
Main Arm Mechanism	1	2.00
Television Camera & Light	3	1.70
Thermal Insulation - Airlock Outer Hatch	1	1.00
Thermal Insulation - Airlock Cylinder	4	1.00
Multi-Layer Insulation	1	1.00
Joint Mechanism	6	1.00
Television Camera Assembly (ITV/LT)	2	1.00
Emergency CO2 Exhaust Nozzle	1	0.75
End Effector	1	0.75
Seal Cover BM Surface	1	0.50
Window Pane	3	0.50
Small Fine Arm	1	0.50
Seal-Airlock Pressure Equalization	1	0.50
Airlock Exhaust Nozzle Heater Element	1	0.30
Television Camera Assembly	3	0.25
CAP (Relief/Vent Dump Valve)	10	0.08
	AVERAGE WORKSITE TIME	1.46

Statistical Discussion of Selected Aspects of ORU Replacement Times and EVA Overhead

A96-J753-STN-M-SLJ-900092

3 May 1990

MEMORANDUM

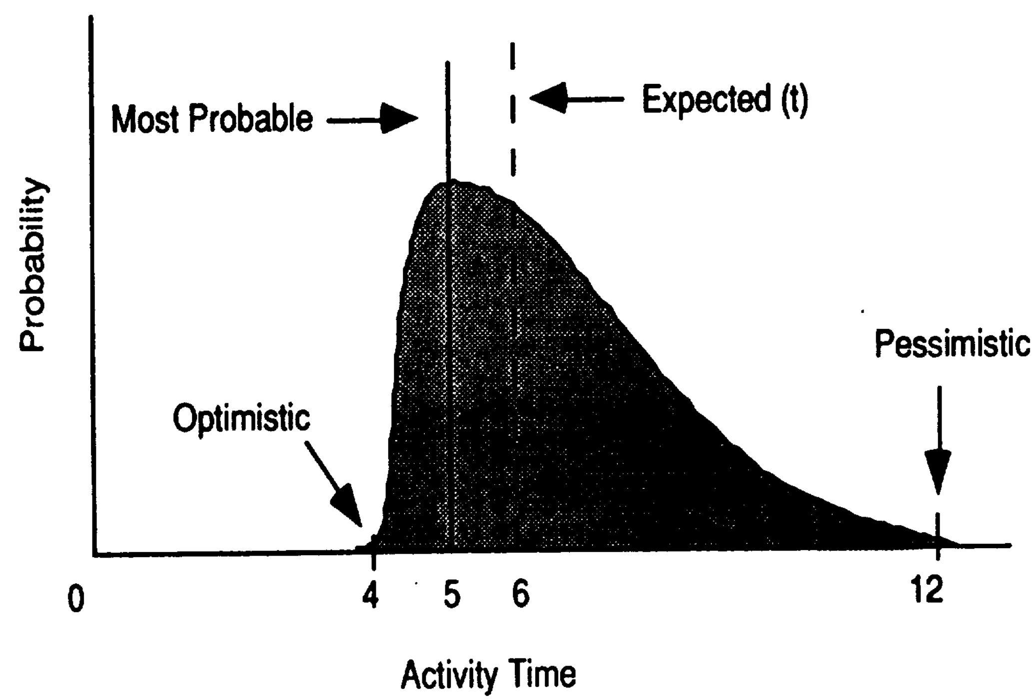
Subject: Beta Distribution Time Estimates for the Generic ITA Maintenance EVA

To: W.F. Fisher, NASA/CB; L. Janicik, NASA/DE42; K. Archard, NASA/DF42; L. Maddox, MDSSC-SSD, HB/17-4; R. Schwarz, NASA/EC5

From: Paul Bailey and Steve Jones, MDSSC

At the recent Fisher-Price midterm review, Karen Archard circulated the Generic ITA Maintenance EVA Procedure, Rev A. We took this procedure and performed a Beta distribution time estimate for each task and formed an overall (entire EVA) estimate summed from the individual task times. We followed standard industry practice in performing the Beta distribution estimate, as is used, for example, in generating a PERT/CPM network for project management.

The Beta distribution is shown in the sketch below. It has been shown through years of industry experience that it represents the probability distribution of tasks times given the following estimation procedure: an expert in the performance of each task is asked to estimate the most optimistic time the task could reasonably be performed in, the most likely (most probable) time the task could be performed in, and the most pessimistic time the task could reasonably be performed in. The skewed Beta distribution, as shown results.



The expected time does not equal the most likely time because the distribution is skewed towards the pessimistic time.Exactly half of all tasks will (by definition) be performed in less than the expected time and half will require more than the expected time. Expected time may be very closely approximated by the following equation:

$t_e = (a+4m+b)/6$

where:

a = optimistic activity time, everything proceeds in an ideal fashion

b = pessimistic time, significant delays encountered

m = most likely activity time under normal conditions

Variance for each task may be calculated by:

$s^2 = ((b - a) / 6)^2$

For each task we estimated the three required times (a, b, m) and calculated the expected time and variance. The time estimates for each task are presented in the enclosure accompanying this memo. It is assumed that all activities are independent of one another, as far as performance time is concerned. If so, the expected time for the entire EVA will simply be the sum of the individual expected times, and the variance for the entire EVA will be the sum of the individual variances. If they are not independent, then the above sums will provide approximations to the total expected time and variance. We assumed independence and calculated expected time and variance for the entire EVA. We calculated standard deviation for the entire EVA by taking the square root of the sums of the variances.

Based on the Central Limit Theorem, which indicates that the sum of independent activity times follows a normal (symmetric bell shaped) distribution as the number of activities becomes large, we assumed a normal distribution for our total EVA time distribution.

Results of our analysis are:

t_e(total) = 5.67 hours

s(total) = 0.27 hours

Using these values, we calculated the probability that the Generic ITA Maintenance EVA would be completed in 6 hours or less. The 6 hour mark represents 1.22 standard deviations above the expected time ((6.00-5.67)/0.27=1.22). From the standard normal distribution tables this yields a probability of 0.39 which, when added to the 0.50 probability of taking 5.67 hours or less, yields a final probability of 0.89 of completing the EVA in 6 hours or less. In other words, 11% of the time it would require more than 6 hours to complete the replacement of 2 ORU's.

A standard procedure in manned spaceflight is to plan for the 3s case, the 99.9% probability case, as the worst case. For our data the 3s case is 6.48 hours. That is, 99.9% of all Generic ITA Maintenance EVA's will be completed in 6.48 hours or less. Only one in a thousand will require more time.

Our conclusion is that, based on our estimates, improvements must be made to the standard EVA procedures to shave a minimum of 30 minutes off the time to replace two ORU's. This will result in a 99.9% chance of meeting the 6 hour time limit on EVA's.

Of course, all times above are, at best, informed guesses which stand in sore need of validation by Neutral Buoyancy Facility tests. We invite others to utilize the above procedure with their own time estimates to arrive at comparison total time distributions. Any questions should be directed to Paul Bailey at (713)283-1944 or Steve Jones at (713)283-1942.

K-Factor

Appendix D

Barry Boswell, P.E.
Space Station Projects Office
NASA Johnson Space Center

July 1990

K-Factor

Abstract

This appendix presents the results of a K-Factor study performed as part of the External Maintenance Task Team (EMTT) effort. The K-Factor accounts for increased equipment maintenance actions resulting from elements which have not been included in the inherent (random) mean-time-between-failure (MTBF) estimates. The K-Factor is used as a multiplier to equipment inherent failure rates in order to determine the required number of maintenance actions over a specified period of time (e.g., per year). The factor is specifically being used in estimating the Space Station Freedom (SSF) Program external maintenance resource demand.

Equipment categories are used as a descriminator to assign K-Factor values. The categories are based on equipment design characteristics. For purposes of this study, six equipment categories have been established. These categories are electrical, electro-mechanical, electronic, mechanical, structural and structural-mechanical. A K-Factor equation has been developed and used for this study. Using the equation, unique K-Factor values have been established for each of these equipment categories.

Constituents of the K-Factor are based on historical definitions and use. Accordingly, items such as human-error-induced damage rates, environment-induced damage rates, interfacing/surrounding-equipment-induced damage rates and no-defect removal rates (attributed to false alarms/incorrect fault isolation and access-caused maintenance actions) have been included in developing the K-Factor values. Historical aircraft data which were directly applicable or correlatable to SSF equipment have been used in developing a portion of the K-Factor values. This included data on human-induced damage rates and false alarm/incorrect isolation rates. Aircraft data on environment-induced damage rates and access-related maintenance actions were considered not applicable or correlatable to the Space Station situation and accordingly were not used in the K-Factor value development. These K-Factor values were developed utilizing SSF design-specific information. The historical aircraft data, referenced in this study, were based on the Air Force AF66-1 database. Maintenance information on the C-5A, C-131E, C-141B, F-16C/D and F-15C/D aircraft was used.

The following results and conclusions were made based on the findings of this study:

1. K-Factor is shown to be a substantial factor when considering total maintenance demands. Human-induced maintenance rates and false maintenance rates historically have been shown as the major drivers. The methodology used to develop the equipment K-Factor values was based on a solid approach. The methodology allows future equipment K-Factor assignments to be made with minimum effort and produces reasonably good results.

2. Certain equipment categories exhibited large K-Factor values. These "heavy hitters" included structural-mechanical equipment (having high human-induced damage rates), mechanical equipment (having high environment-induced damage rates), and electronic equipment (having high environmental and no-defect removal rates).
3. The total K-Factor value (for the various equipment categories) ranged from 1.51 to 3.11. This range is consistent with what has been repeatedly verified on major programs in which maintenance data have been tracked.

The following recommendations were made based on the results and conclusions of this study:

1. The results of this study should be used to provide design direction for various SSF equipment. If emphasis is applied on the items driving K-Factor values, reduced maintenance demand will result.
2. A detailed study of human error should be performed to gain better understanding of drivers which cause humans to err in the space environment. Once the drivers are singled out, design efforts should be made to accommodate and reduce the causes. The detailed study is recommended because human-error-induced rates are a significant portion of the overall K-Factor totals. This is related to the design of common ORUs, tools, and maintenance procedures.
3. With the appreciable effects of ionizing radiation on electronic equipment, and because SSF has many electronic devices located in the external environment, stringent equipment radiation-hardening specifications/processes should be considered.
4. As analyses (such as the FMEAs and CILs) are completed, the ratio used in developing the environment-induced portion of the K-Factor values should be revisited. This is needed because the ratio turns out to be a driving element in the value development. Also, consider requirements for non-critical equipment (e.g., 95% for criticality 1R, etc.).
5. The SSF program should have an effective tracking program and database so that future manned space programs will have quantifiable and traceable maintenance information for use in estimating resource demands. This data will also provide for monitoring SSF Program trends and allow personnel to be alerted to any developing adverse trend conditions. Establish possible "alarm levels" beyond which corrective action/investigation would be required.

Introduction

This report presents the K-Factor development process, definitions, equations, supporting data sources, data findings, results, and recommendations of this K-Factor Study.

Statement of Problem

Uncertainties exist regarding maintenance actions because the capability required of the program is dependent on more than the inherent reliability of the system. Other factors, such as induced failures and false maintenance actions, must be included to correctly scope the maintenance resources required. At present, inconsistencies exist across the program with regard to the definition, application, and quantification of this factor.

Approach

The following ground rules and assumptions were made for this study. Each is elaborated on within appropriate sections of this report.

The K-Factor is a factor that accounts for increased equipment maintenance actions resulting from elements which have not been included in the inherent (random) MTBF estimates. The K-Factor is used as a multiplier to the equipment inherent maintenance rates. The factor is being used in estimating the SSF Program extravehicular activity (EVA) maintenance resource demand.

Preventive maintenance, inspection, and overhead rates/times are not included as part of the K-Factor. Each is being independently determined and appropriately implemented into the EMTT EVA demand equation (referenced from EMTT report to John Aaron on 2/27/90).

The SSF equipment can be classified into various categories. For purposes of this study, six equipment categories have been established. These categories consist of electrical, electro-mechanical, electronic, mechanical, structural, and structural-mechanical. A unique K-Factor value has been established for each category of equipment. It can be noted that major aircraft systems (i.e., environmental control, communications, navigation, hydraulic, propulsion, and others) historically have a unique total K-Factor value associated with them. However, if system representative historical values were used to derive the SSF system K-Factor values, large errors could occur due to the dissimilarities (in both equipment type and quantities) existing at these major system levels. Accordingly, this study's objective is to suboptimize evaluations at the equipment-type level. This approach allows for major system value development if desired, but, more importantly, it yields better qualified estimates.

Elements and subelements of the K-Factor are based on historical definitions and use. Accordingly, items such as human-error-induced damage rates, environment-induced damage rates, interfacing/surrounding equipment-induced damage rates and no-defect removal rates (attributed to false alarms/incorrect fault isolation and access-caused maintenance actions) have been included in developing K-Factor values. Historical aircraft data which were directly applicable or correlatable to SSF have been used in developing K-Factor values. This included data on human-induced causes for maintenance actions and false maintenance actions. Aircraft data which were considered not applicable or correlatable were omitted. This included data on environment-induced and access-related maintenance actions. These K-Factor elements and subelements were developed utilizing SSF design-specific information. The historical data referenced in this study were based on the Air Force AF66-1 database. Maintenance information on the C-5A, C-131E, C-141B, F-16C/D and F-15C/D aircraft was used.

False maintenance rates, due to false alarms and incorrect fault isolation, are considered similar when comparing aircraft to SSF equipment. This is because a significant portion of the software and hardware being used for SSF built-in test (BIT) is commercial off-the-shelf (COTS). The additional SSF specifically developed software and hardware have been evaluated, and it is expected that a more effective BIT will be generated compared to the previous editions. Accordingly, the aircraft historical data have been used as a baseline. The baseline data was then modified (for the additional BIT capabilities being implemented on SSF) using a correlation factor. This correlation factor transforms the aircraft data into the SSF application.

Good design practice facilitates that higher failure rate items are more readily accessible than low failure rate items. This practice typically produces lower maintenance times. Occasionally these higher failure rate items must be removed to gain access to a failed lower failure rate item. These additional removals are currently being accounted for in the equipment K-Factor value. Historically, access-caused maintenance actions to equipment have been significant. Reasons for this stem from the fact that aircraft requirements typically do not dictate that in-the-way removals are prohibited. Accordingly, the access-caused rates for aircraft are relatively high. Access requirements for SSF equipment, however, are quite explicit. The design is to be such that it is not necessary to remove equipment when performing maintenance on other surrounding equipment. Currently, however, some SSF equipment has been identified which occasionally does require removal to gain access to other equipment. It can be noted that these cases are minimal and mainly have to do with meeting performance requirements. It is expected that these cases will be fully justified so as to allow deviation waivers to be granted. An access-caused rate has been estimated for each of the various SSF equipment-type categories.

Equipment types have unique failure modes which drive the potential for secondary damage and cascading failures. However, it should be noted that specific Space Station requirements have been imposed on the program which substantially reduce the probability of equipment-induced damage occurrence. Upon a cursory review of the various Space Station equipment design philosophies and design provisions, it is realistically expected that equipment-induced damage of other interfaced and surrounding equipment will be negligible.

Results and Discussion

K-Factor Elements and Subelements

The following defines the elements and subelements used in the K-Factor study. These items each contribute to the total maintenance rate expected for Space Station Freedom equipment.

Induced-Damage Rate Element. Three subelements contribute to equipment-induced damages. These subelements include human error, environmental factors, and interfacing/surrounding equipment-induced failures. The following describes these subelements.

Human-Error-Induced Damage. Any inadvertent human-induced damage which occurs to a piece of equipment resulting from operation, maintenance activities, and/or incidental contact. This includes things such as damage caused by misuse of equipment and tools, accidental tool release, inadequate instruction/training, and any severe accidental contact made during equipment handling or crew translations. Causes contributing to human error include visibility/perception, mobility/dexterity, comfort, fatigue, training, motivation, and crew member position orientation.

Environment-Induced Damage. Any equipment damage resulting from a surrounding environment which is not accounted for in the inherent (random) MTBF. Examples of this would include foreign object damage (due to micrometeoroids/space debris) and ionizing radiation.

Equipment-Induced Damage. Any equipment damage occurring to one piece of equipment as the result of a failure or malfunction of another piece of equipment. This subelement considers secondary failures and cascading failures which may occur due to interfacing and/or surrounding equipment.

No-Defect Rate Element. Three subelements contribute to maintenance rates of equipment when, in reality, a no-defect condition exists. Items causing such circumstances include false alarms, incorrect fault isolation and in-the-way removals. For purposes of consistency with the historical data findings, the false alarms and incorrect isolations have been combined into one subelement for the evaluations.

False Alarms. False alarms are produced when an anomaly exists in BIT functionality. This causes an operational failure indication when one does not truly exist. Any maintenance actions resulting from these indications contribute to the no-defect maintenance rate. These occurrences can be due to software latent errors and hardware circuitry causes.

Incorrect Fault Isolation. Any maintenance action resulting from incorrect identification to a failed piece of equipment. This includes ambiguity groups where detection circuits are unable to positively locate the fault to an ORU. Incorrect automatic isolation occurrence can be due to software/hardware causes. Incorrect manual isolation can be due to troubleshooting procedure problems or faulty test equipment.

In-the-Way Removals. Any maintenance action which occurs to one piece of equipment to allow access for troubleshooting or maintenance of another piece of equipment.

K-Factor Equation

The K-Factor equation used in this study is defined as:

$$K = (K1 + K2 + K3 + K4) + 1$$

Where:

K	is the equipment type total K-Factor value
K1	is the human-error-induced subelement value
K2	is the environment-induced subelement value
K3	is the equipment-induced subelement value
K4	is the total no-defect rate element value
1	accounts for the equipment inherent maintenance action rate

Note: The K-Factor element and subelement values are derived based on relative ratios to the inherent maintenance rate. Each ratio is rounded to the nearest two decimal places.

The following example demonstrates the K-Factor concept and use of the equation:

Given: 28 equipment maintenance actions occurred on an aircraft wiring harness type during a reporting period. Upon review, it was determined that 15 actions were due to equipment inherent causes. The other 13 maintenance actions were attributable to K-Factor elements/subelements. The K-Factor relative ratio values were determined as follows:

Element	# Actions	Values
Human-induced (K1)	6	0.40
Environment-induced (K2)	0	0.00
Equipment-induced (K3)	0	0.00
No-Defect Maintenance (K4)	7	0.47
	13	0.87

Now using the equation:

$$K = (.40 + .00 + .00 + .47) + 1$$
$$= \underline{1.87}$$

Note: The harness is considered within the electrical category and, accordingly, is used in the development of the electrical category K-Factor value. For clarity, the example shown does not include application of any correlation factors.

Once each equipment category (i.e., mechanical, electrical, etc.) total K-Factor value is established, it is to be inserted into the EMTT Database against the appropriate equipment within each category. For instance, each piece of equipment identified in the "mechanical" type category will have the appropriate "mechanical" K-Factor value applied to it. After all the K-Factor values have been inserted, the total SSF EVA demand can be estimated.

Equipment Classifications

Categories are being used as a descriptor to assign K-Factor values. The categories are based on equipment design characteristics. The ORU Database has defined these categories as equipment "Reliability Types." All equipment is classified within one of the six following categories:

Electrical

Electrical-mechanical (Electromech)

Electronic

Mechanical

Structural

Structural-mechanical (Structmech)

The following criteria have been used to characterize the historical aircraft and current SSF equipment. These criteria are to be used to categorize newly developed SSF equipment in the future.

Electrical: Electrical equipment is that which performs electrical power distribution or storage functions, signal distribution, or radio frequency radiation functions, and approximately 5% or less of the failure rate is due to digital or low-power electronics or moving parts. Typically, electrical types are selected where a low level of BIT is utilized.

Electronic: Electronic equipment is that which is primarily digital or analog circuitry in nature and has a greater need for BIT than the electrical type.

The equipment is classified as electronic only if less than 5% of the failure rate is due to moving parts.

Mechanical: Mechanical equipment is that which typically consists of moving parts or contains fluids or seals. This type of equipment must contain less than 5% of the failure rate due to electrical or electronic parts. Heat-transfer-type equipment is classified as mechanical.

Structural: Structural equipment is that which is load bearing and less than 5% of the failure rate is due to moving parts or sensory components. (However, a moving part may be contained within a structure if the moving part is a separate piece of equipment.) Structure, as defined in this study, is further characterized as not typically having crew contact. It is noted that the truss struts will occasionally be used by crew members during translation. However, since the struts are being designed to accommodate inadvertent impacts and loads which can be produced by humans in space suits, they are being classified in the structure category.

Electromech: Electromech equipment is that which contains both electrical/electronic and mechanical moving parts. This includes devices which typically utilize electrical energy to produce mechanical motion and those which use mechanical energy to produce electrical power or signals. These devices should contain more than 5% of mechanical and 5% electrical (or electronic) parts (based on failure rate).

Structmech: Structmech equipment is that which is mostly structural or designed for equipment protection and typically involves crew interaction. This type of equipment specifically includes items such as doors, covers, panels, meteoroid/debris shields, thermal blankets, handrails, foot restraints and other equipment involving frequent crew contact. The main difference between structural and structural-mechanical is that the latter contains moving parts and/or fasteners which are inherently more vulnerable to damage during human contact.

K-Factor Development Process

The following methodology was used to develop K-Factor values for Space Station Freedom equipment types:

A) Defined K-Factor elements/subelements and the K-Factor equation.

B) Gathered and evaluated historical data on aircraft equipment maintenance and categorized the equipment and data by K-Factor elements/subelements.

C) Summed K-Factor element/subelement values for each equipment type (i.e., control panels, heat exchangers, valves, actuators, controllers, etc.).

D) Grouped historical equipment into classifications and averaged the K-Factor subelement values to yield representative total subelement values.

E) Defined equipment classifications (i.e., mechanical, electrical, structural, etc.) based on reliability types for various SSF equipment.

F) Developed and applied correlation factors for human error and false maintenance rates to the historical aircraft K-Factor subelements to yield a SSF equipment equivalent.

G) Developed the K-Factor subelement values for environment-induced, equipment-induced and access-caused maintenance actions.

H) Established a matrix reflecting the various subelement and total K-Factor values for each reliability classification type.

HISTORICAL K-FACTOR DATA SHEET

Equipment: BULKHEAD	Reliability Type: Structural/Mechanical	Correlation Factors	
Comments: Loose/damaged hardware.		Human-Induced:	1.10
		Environment-Induced:	0.00
		Equipment-Induced:	0.00
		False Maintenance:	1.00
		Access Maintenance:	0.00

System/ Model	WUC	Quantity of Maintenance Actions						K-Factor Element Values				
		Inherent Cause	Human-Induced	Env.-Induced	Equip.-Induced	False Maint.	Access Maint.	K1	K2	K3	K4 False	K4 Access
C-5A	11TUG	196	315	0	0	69	0	1.61	0	0	0.35	0
C-5A	11TUH	187	291	0	0	32	0	1.56	0	0	0.17	0
F-16C/D	11AAB	3	6	0	0	0	0	2.00	0	0	0	0
F-16C/D	11GAP	2	5	0	0	0	0	2.50	0	0	0	0
F-15C/D	11DAJ	8	7	0	0	1	1	0.88	0	0	0.13	0.13
F-15C/D	11DAK	1	2	0	0	0	2	2.00	0	0	0	2.00
F-15C/D	11GBB	1	1	0	0	0	0	1.00	0	0	0	0
								NA	NA	NA	NA	NA
								NA	NA	NA	NA	NA
								NA	NA	NA	NA	NA
								NA	NA	NA	NA	NA
								NA	NA	NA	NA	NA
								NA	NA	NA	NA	NA
								NA	NA	NA	NA	NA
								NA	NA	NA	NA	NA
								NA	NA	NA	NA	NA
							Average	1.65	0.00	0.00	0.09	0.13
							Correlated	1.82	0.00	0.00	0.09	0.00

HISTORICAL K-FACTOR DATA SHEET

Equipment: CABLE/HARNESS	Reliability Type: Electrical (power)	Correlation Factors	
Comments: Loose/damaged hardware.		Human-Induced:	1.10
		Environment-Induced:	0.00
		Equipment-Induced:	0.00
		False Maintenance:	0.90
		Access Maintenance:	0.00

System/ Model	WUC	Quantity of Maintenance Actions						K-Factor Element Values				
		Inherent Cause	Human-Induced	Env.-Induced	Equip.-Induced	False Maint.	Access Maint.	K1	K2	K3	K4 False	K4 Access
C-5A	42NAO	9	4	0	0	6	0	0.44	0	0	0.67	0
C-5A	46GBJ	3	0	0	0	1	0	0	0	0	0.33	0
C-5A	42NCO	6	2	0	0	3	0	0.33	0	0	0.50	0
C-5A	42NEO	3	0	0	0	1	0	0	0	0	0.33	0
C-5A	41JDM	2	0	0	0	0	0	0	0	0	0	0
C-5A	55AQG	2	0	0	0	0	0	0	0	0	0	0
C-130E	32536	15	6	0	0	7	0	0.40	0	0	0.47	0
C-130E	12BCC	2	0	0	0	0	0	0	0	0	0	0
C-141B	42EAC	18	1	0	0	4	0	0.06	0	0	0.22	0
C-141B	42GAK	1	0	0	0	0	0	0	0	0	0	0
F-16C/D	24DFD	18	0	0	0	0	0	0	0	0	0	0
F-16C/D	74ASD	2	0	0	0	2	0	0	0	0	1.00	0
F-16C/D	24DFC	2	0	0	0	1	0	0	0	0	0.50	0
F-16C/D	23KAG	17	2	0	0	9	0	0.12	0	0	0.53	0
F-15C/D	44EDO	2	0	0	0	1	0	0	0	0	0.50	0
F-15C/D	13ALO	23	3	0	0	5	1	0.13	0	0	0.22	0.04
						Average		0.09	0.00	0.00	0.33	0.00
						Correlated		0.10	0.00	0.00	0.30	0.00

HISTORICAL K-FACTOR DATA SHEET

Equipment: CONTROL PANEL	Reliability Type: Electrical	Correlation Factors	
Comments: Loose/damaged hardware.		Human-Induced:	1.10
		Environment-Induced:	0.00
		Equipment-Induced:	0.00
		False Maintenance:	0.90
		Access Maintenance:	0.00

System/ Model	WUC	Quantity of Maintenance Actions						K-Factor Element Values				
		Inherent Cause	Human-Induced	Env.-Induced	Equip.-Induced	False Maint.	Access Maint.	K1	K2	K3	K4 False	K4 Access
C-5A	52JCO	84	2	0	0	59	0	0.02	0	0	0.70	0
C-5A	66ACO	66	20	0	0	20	0	0.30	0	0	0.30	0
C-130E	49116	2	0	0	0	2	0	0	0	0	1.00	0
C-141B	42DBC	3	0	0	0	1	0	0	0	0	0.33	0
C-141B	52EFO	78	4	0	0	30	0	0.05	0	0	0.38	0
C-141B	71AAC	136	56	0	0	12	0	0.41	0	0	0.09	0
F-16C/D	44BAO	23	0	0	0	6	2	0	0	0	0.26	0.09
F-16C/D	44BBO	7	0	0	0	1	2	0	0	0	0.14	0.29
F-16C/D	12AED	4	0	0	0	2	0	0	0	0	0.50	0
F-16C/D	13AAC	13	0	0	0	5	0	0	0	0	0.38	0
F-16C/D	41ACA	5	0	0	0	1	1	0	0	0	0.20	0.20
F-16C/D	14ADO	47	0	0	0	24	17	0	0	0	0.51	0.36
F-15C/D	44BAR	14	0	0	0	3	1	0	0	0	0.21	0.07
F-15C/D	44BAV	6	2	0	0	0	0	0.33	0	0	0	0
F-15C/D	44BBO	17	2	0	0	7	0	0.12	0	0	0.41	0
F-15C/D	42BCO	1	0	0	0	0	0	0	0	0	0	0
						Average		0.08	0.00	0.00	0.34	0.06
						Correlated		0.09	0.00	0.00	0.31	0.00

HISTORICAL K-FACTOR DATA SHEET

Equipment: CONTROLLER	Reliability Type: Electronic	Correlation Factors	
Comments: Loose/damaged hardware.		Human-Induced:	1.10
		Environment-Induced:	0.00
		Equipment-Induced:	0.00
		False Maintenance:	0.90
		Access Maintenance:	0.00

System/ Model	WUC	Quantity of Maintenance Actions						K-Factor Element Values				
		Inherent Cause	Human-Induced	Env.-Induced	Equip.-Induced	False Maint.	Access Maint.	K1	K2	K3	K4 False	K4 Access
C-5A	42JAC	144	2	0	0	19	0	0.01	0	0	0.13	0
C-5A	13TGO	1	0	0	0	0	0	0	0	0	0	0
C-5A	42EAP	324	11	0	0	78	0	0.03	0	0	0.24	0
C-5A	64CCO	2	1	0	0	0	0	0.50	0	0	0	0
C-130E	72NAB	13	1	0	0	1	0	0.08	0	0	0.08	0
C-130E	72NAC	8	2	0	0	0	0	0.25	0	0	0	0
C-141B	71AAC	136	56	0	0	12	0	0.41	0	0	0.09	0
C-141B	52EFO	78	4	0	0	30	0	0.05	0	0	0.38	0
C-141B	42DBC	3	0	0	0	1	0	0	0	0	0.33	0
C-141B	44BBA	50	3	0	0	5	0	0.06	0	0	0.10	0
F-16C/D	24CBO	12	0	0	0	28	2	0	0	0	2.33	0.17
F-16C/D	24DCO	48	5	0	0	31	12	0.10	0	0	0.65	0.25
F-16C/D	41ACM	12	0	0	0	2	0	0	0	0	0.17	0
F-16C/D	13EAD	33	7	0	0	17	0	0.21	0	0	0.52	0
F-16C/D	14AAO	95	0	0	0	117	48	0	0	0	1.23	0.51
F-16C/D	14FCO	11	0	0	0	10	28	0	0	0	0.91	2.55
						Average		0.11	0.00	0.00	0.45	0.22
						Correlated		0.12	0.00	0.00	0.41	0.00

HISTORICAL K-FACTOR DATA SHEET

Equipment: DATABUS	Reliability Type: Electrical	Correlation Factors	
Comments: Loose/damaged hardware.		Human-Induced:	1.10
		Environment-Induced:	0.00
		Equipment-Induced:	0.00
		False Maintenance:	0.90
		Access Maintenance:	0.00

System/ Model	WUC	Quantity of Maintenance Actions						K-Factor Element Values				
		Inherent Cause	Human-Induced	Env.-Induced	Equip.-Induced	False Maint.	Access Maint.	K1	K2	K3	K4 False	K4 Access
C-5A	71DAB	8	11	0	0	0	0	1.38	0	0	0	0
C-5A	62BAC	6	2	0	0	0	0	0.33	0	0	0	0
C-5A	61AAH	34	12	0	0	3	0	0.35	0	0	0.09	0
C-141B	65BAE	10	8	0	0	1	0	0.80	0	0	0.10	0
F-16C/D	74ZDO	2	1	0	0	0	0	0.50	0	0	0	0
F-16C/D	74ZOO	1	0	0	0	1	0	0	0	0	1.00	0
F-16C/D	74ZAO	2	0	0	0	1	0	0	0	0	0.50	0
F-16C/D	42DAB	3	1	0	0	2	0	0.33	0	0	0.67	0
F-16C/D	42DBA	1	0	0	0	1	0	0	0	0	1.00	0
F-16C/D	63BKN	3	0	0	0	0	0	0	0	0	0	0
								NA	NA	NA	NA	NA
								NA	NA	NA	NA	NA
								NA	NA	NA	NA	NA
								NA	NA	NA	NA	NA
								NA	NA	NA	NA	NA
								NA	NA	NA	NA	NA
						Average		0.37	0.00	0.00	0.34	0.00
						Correlated		0.41	0.00	0.00	0.31	0.00

HISTORICAL K-FACTOR DATA SHEET

Equipment: DUCT	Reliability Type: Structural
Comments: Loose/damaged hardware.	

Correlation Factors	
Human-Induced:	1.10
Environment-Induced:	0.00
Equipment-Induced:	0.00
False Maintenance:	1.00
Access Maintenance:	0.00

System/ Model	WUC	Quantity of Maintenance Actions						K-Factor Element Values				
		Inherent Cause	Human-Induced	Env.-Induced	Equip.-Induced	False Maint.	Access Maint.	K1	K2	K3	K4 False	K4 Access
C-5A	41ATA	11	4	0	0	1	0	0.36	0	0	0.09	0
C-5A	41ATB	5	3	0	0	5	0	0.60	0	0	1.00	0
C-5A	41AWB	17	19	0	0	9	0	1.12	0	0	0.53	0
C-5A	41AWA	43	42	0	0	25	0	0.98	0	0	0.58	0
C-130E	41131	45	33	0	0	49	0	0.73	0	0	1.09	0
C-130E	41231	27	16	0	0	13	0	0.59	0	0	0.48	0
C-130E	41431	55	8	0	0	55	0	0.15	0	0	1.00	0
C-141B	23LSO	9	10	0	0	3	0	1.11	0	0	0.33	0
C-141B	41DCC	33	34	0	0	24	0	1.03	0	0	0.73	0
F-16C/D	41AAL	28	58	0	0	12	10	2.07	0	0	0.43	0.36
F-15C/D	41AA1	14	2	1	0	2	5	0.14	0.07	0	0.14	0.36
F-15C/D	23QAH	2	0	0	0	1	0	0	0	0	0.50	0
F-15C/D	23QAM	8	0	0	0	1	1	0	0	0	0.13	0.13
F-15C/D	23QAV	1	0	0	0	0	0	0	0	0	0	0
F-15C/D	23QCO	1	0	0	0	0	0	0	0	0	0	0
F-15C/D	24CAB	41	6	0	0	19	2	0.15	0	0	0.46	0.05
						Average		0.56	0.01	0.00	0.47	0.06
						Correlated		0.62	0.00	0.00	0.47	0.00

HISTORICAL K-FACTOR DATA SHEET

Equipment: ELECT. RECEPTACLE	Reliability Type: Electrical	Correlation Factors	
Comments: Loose/damaged hardware.		Human-Induced:	1.10
		Environment-Induced:	0.00
		Equipment-Induced:	0.00
		False Maintenance:	0.90
		Access Maintenance:	0.00

System/ Model	WUC	Quantity of Maintenance Actions						K-Factor Element Values				
		Inherent Cause	Human-Induced	Env.-Induced	Equip.-Induced	False Maint.	Access Maint.	K1	K2	K3	K4 False	K4 Access
C-5A	46HAQ	6	0	0	0	1	0	0	0	0	0.17	0
C-5A	44AQC	25	6	0	0	0	0	0.24	0	0	0	0
C-5A	46HAA	14	7	0	0	6	0	0.50	0	0	0.43	0
C-130E	42231	11	8	0	0	0	0	0.73	0	0	0	0
C-130E	51XAO	20	4	0	0	2	0	0.20	0	0	0.10	0
C-141B	64AAN	41	13	0	0	2	0	0.32	0	0	0.05	0
C-141B	64AAL	65	39	0	0	3	0	0.60	0	0	0.05	0
F-16C/D	42ECO	1	0	0	0	2	0	0	0	0	2.00	0
F-16C/D	23KAR	6	0	0	0	1	0	0	0	0	0.17	0
F-15C/D	42BBO	1	0	0	0	1	0	0	0	0	1.00	0
C-5A	44CYL	5	2	0	0	0	0	0.40	0	0	0	0
C-5A	44CUF	5	0	0	0	1	0	0	0	0	0.20	0
								NA	NA	NA	NA	NA
								NA	NA	NA	NA	NA
								NA	NA	NA	NA	NA
								NA	NA	NA	NA	NA
						Average		0.25	0.00	0.00	0.35	0.00
						Correlated		0.28	0.00	0.00	0.32	0.00

HISTORICAL K-FACTOR DATA SHEET

Equipment: FRAME/RACK	Reliability Type: Structural	Correlation Factors	
Comments: Loose/damaged hardware.		Human-Induced:	1.10
		Environment-Induced:	0.00
		Equipment-Induced:	0.00
		False Maintenance:	1.00
		Access Maintenance:	0.00

System/ Model	WUC	Quantity of Maintenance Actions						K-Factor Element Values				
		Inherent Cause	Human-Induced	Env.-Induced	Equip.-Induced	False Maint.	Access Maint.	K1	K2	K3	K4 False	K4 Access
C-5A	11UAD	13	3	0	0	0	0	0.23	0	0	0	0
C-5A	11SFC	5	3	0	0	0	0	0.60	0	0	0	0
C-5A	11SLC	19	6	0	0	2	0	0.32	0	0	0.11	0
C-5A	11SRC	25	8	0	0	6	0	0.32	0	0	0.24	0
C-130E	11611	8	3	0	0	1	0	0.38	0	0	0.13	0
C-130E	14137	7	3	0	0	1	0	0.43	0	0	0.14	0
C-130E	4123B	3	0	0	0	0	0	0	0	0	0	0
C-130E	11311	84	36	0	0	21	0	0.43	0	0	0.25	0
C-141B	11BAJ	23	11	0	0	2	0	0.48	0	0	0.09	0
C-141B	11CAA	12	8	0	0	1	0	0.67	0	0	0.08	0
C-141B	11CGA	1	0	0	0	0	0	0	0	0	0	0
C-141B	11EAA	43	13	0	0	1	0	0.30	0	0	0.02	0
F-16C/D	74DCO	1	0	0	0	0	0	0	0	0	0	0
F-16C/D	11JAA	2	0	0	0	0	0	0	0	0	0	0
F-15C/D	11AFA	3	0	0	0	5	0	0	0	0	1.67	0
F-15C/D	12CAB	13	10	1	0	4	0	0.77	0.08	0	0.31	0
						Average		0.31	0.01	0.00	0.19	0.00
						Correlated		0.34	0.00	0.00	0.19	0.00

HISTORICAL K-FACTOR DATA SHEET

Equipment: HEAT EXCH./COOLER	Reliability Type: Mechanical
Comments: Loose/damaged hardware.	

Correlation Factors	
Human-Induced:	1.10
Environment-Induced:	0.00
Equipment-Induced:	0.00
False Maintenance:	1.00
Access Maintenance:	0.00

System/ Model	WUC	Quantity of Maintenance Actions						K-Factor Element Values				
		Inherent Cause	Human-Induced	Env-Induced	Equip.-Induced	False Maint.	Access Maint.	K1	K2	K3	K4 False	K4 Access
C-5A	45LAF	4	10	0	0	1	0	2.50	0	0	0.25	0
C-5A	41AWE	21	17	0	0	8	0	0.81	0	0	0.38	0
C-5A	49BBD	2	1	0	0	2	0	0.50	0	0	1.00	0
C-130E	41PAB	1	0	0	0	0	0	0	0	0	0	0
C-130E	41141	24	9	0	0	12	0	0.38	0	0	0.50	0
C-130E	41251	30	13	0	0	10	0	0.43	0	0	0.33	0
C-141B	47AAC	5	2	0	0	5	0	0.40	0	0	1.00	0
C-141B	41ADB	32	7	0	0	8	0	0.22	0	0	0.25	0
C-141B	41ADC	8	3	0	0	3	0	0.38	0	0	0.38	0
F-16C/D	23JAC	1	0	0	0	0	0	0	0	0	0	0
F-15C/D	24ANU	4	0	0	0	0	0	0	0	0	0	0
F-15C/D	41CCD	9	0	0	0	0	0	0	0	0	0	0
								NA	NA	NA	NA	NA
								NA	NA	NA	NA	NA
								NA	NA	NA	NA	NA
								NA	NA	NA	NA	NA
							Average	0.47	0.00	0.00	0.34	0.00
							Correlated	**0.52**	**0.00**	**0.00**	**0.34**	**0.00**

HISTORICAL K-FACTOR DATA SHEET

Equipment: HEATER	Reliability Type: Electrical	Correlation Factors	
Comments: Loose/damaged hardware.		Human-Induced:	1.10
		Environment-Induced:	0.00
		Equipment-Induced:	0.00
		False Maintenance:	0.90
		Access Maintenance:	0.00

System/ Model	WUC	Quantity of Maintenance Actions						K-Factor Element Values				
		Inherent Cause	Human-Induced	Env.-Induced	Equip.-Induced	False Maint.	Access Maint.	K1	K2	K3	K4 False	K4 Access
C-5A	12DAM	5	0	0	0	1	0	0	0	0	0.20	0
C-5A	12DAQ	15	3	0	0	3	0	0.20	0	0	0.20	0
F-16C/D	42JBB	1	0	0	0	0	0	0	0	0	0	0
								NA	NA	NA	NA	NA
								NA	NA	NA	NA	NA
								NA	NA	NA	NA	NA
								NA	NA	NA	NA	NA
								NA	NA	NA	NA	NA
								NA	NA	NA	NA	NA
								NA	NA	NA	NA	NA
								NA	NA	NA	NA	NA
								NA	NA	NA	NA	NA
								NA	NA	NA	NA	NA
								NA	NA	NA	NA	NA
								NA	NA	NA	NA	NA
								NA	NA	NA	NA	NA
							Average	0.07	0.00	0.00	0.13	0.00
							Correlated	0.08	0.00	0.00	0.12	0.00

HISTORICAL K-FACTOR DATA SHEET

Equipment: HOSE	Reliability Type: Mechanical	Correlation Factors	
Comments: Loose/damaged hardware.		Human-Induced:	1.10
		Environment-Induced:	0.00
		Equipment-Induced:	0.00
		False Maintenance:	1.00
		Access Maintenance:	0.00

System/ Model	WUC	Quantity of Maintenance Actions						K-Factor Element Values				
		Inherent Cause	Human-Induced	Env.-Induced	Equip.-Induced	False Maint.	Access Maint.	K1	K2	K3	K4 False	K4 Access
C-5A	45AJV	35	16	0	0	6	0	0.46	0	0	0.17	0
C-5A	45JAP	3	0	0	0	2	0	0	0	0	0.67	0
C-5A	45CJT	44	21	0	0	10	0	0.48	0	0	0.23	0
C-5A	13BEH	15	3	0	0	5	0	0.20	0	0	0.33	0
C-130E	1413J	82	1	0	0	36	0	0.01	0	0	0.44	0
C-130E	1423H	12	1	0	0	3	0	0.08	0	0	0.25	0
C-130E	1433H	23	0	0	0	9	0	0	0	0	0.39	0
C-130E	14428	73	5	0	0	31	0	0.07	0	0	0.42	0
C-130E	2213L	49	13	0	0	8	0	0.27	0	0	0.16	0
C-130E	22160	29	10	0	0	7	0	0.34	0	0	0.24	0
C-141B	45EAM	23	5	0	0	11	0	0.22	0	0	0.48	0
C-141B	45BEM	38	18	0	0	15	0	0.47	0	0	0.39	0
C-141B	45CFF	45	17	0	0	19	0	0.38	0	0	0.42	0
C-141B	41AFJ	1	0	0	0	0	0	0	0	0	0	0
F-16C/D	47AEO	4	3	0	0	4	0	0.75	0	0	1.00	0
F-15C/D	41ABE	8	0	0	0	1	0	0	0	0	0.13	0
						Average		0.23	0.00	0.00	0.36	0.00
						Correlated		0.25	0.00	0.00	0.36	0.00

HISTORICAL K-FACTOR DATA SHEET

Equipment: LIGHT	Reliability Type: Electrical	Correlation Factors	
Comments: Loose/damaged hardware.		Human-Induced:	1.10
		Environment-Induced:	0.00
		Equipment-Induced:	0.00
		False Maintenance:	0.90
		Access Maintenance:	0.00

System/ Model	WUC	Quantity of Maintenance Actions						K-Factor Element Values				
		Inherent Cause	Human-Induced	Env.-Induced	Equip.-Induced	False Maint.	Access Maint.	K1	K2	K3	K4 False	K4 Access
C-5A	44AEC	114	44	0	0	9	0	0.39	0	0	0.08	0
C-5A	44AEA	232	138	0	0	18	0	0.59	0	0	0.08	0
C-5A	44DEA	298	76	0	0	23	0	0.26	0	0	0.08	0
C-130E	44165	119	67	0	0	4	0	0.56	0	0	0.03	0
C-130E	44236	35	12	0	0	2	0	0.34	0	0	0.06	0
C-130E	44241	23	8	0	0	1	0	0.35	0	0	0.04	0
C-130E	44271	177	45	0	0	2	0	0.25	0	0	0.01	0
C-130E	44281	65	16	0	0	4	0	0.25	0	0	0.06	0
F-16C/D	44AAA	150	19	0	0	2	0	0.13	0	0	0.01	0
F-16C/D	44AAC	21	2	0	0	2	0	0.10	0	0	0.10	0
F-16C/D	44BCO	26	2	0	0	3	0	0.08	0	0	0.12	0
F-15C/D	44AAC	495	40	0	0	37	17	0.08	0	0	0.07	0.03
F-15C/D	44AAL	385	33	0	0	49	7	0.09	0	0	0.13	0.02
F-15C/D	44AAV	28	2	0	0	6	0	0.07	0	0	0.21	0
F-15C/D	44AAX	31	1	0	1	3	0	0.03	0	0.03	0.10	0
F-15C/D	44BAA	27	1	0	0	2	0	0.04	0	0	0.07	0
						Average		0.22	0.00	0.00	0.08	0.00
						Correlated		0.24	0.00	0.00	0.07	0.00

HISTORICAL K-FACTOR DATA SHEET

Equipment: PANEL/DOOR/COVER	Reliability Type: Structural/Mechanical	Correlation Factors	
Comments: Loose/damaged hardware.		Human-Induced:	1.10
		Environment-Induced:	0.00
		Equipment-Induced:	0.00
		False Maintenance:	1.00
		Access Maintenance:	0.00

System/ Model	WUC	Quantity of Maintenance Actions						K-Factor Element Values				
		Inherent Cause	Human-Induced	Env.-Induced	Equip.-Induced	False Maint.	Access Maint.	K1	K2	K3	K4 False	K4 Access
C-5A	11SCH	22	42	0	0	58	0	1.91	0	0	2.64	0
C-5A	11SEH	23	53	0	0	18	0	2.30	0	0	0.78	0
C-5A	11SGG	21	60	0	0	36	0	2.86	0	0	1.71	0
C-5A	11SJH	10	31	0	0	8	0	3.10	0	0	0.80	0
C-5A	11UAG	53	101	0	0	34	0	1.91	0	0	0.64	0
C-130E	1142R	24	43	0	0	23	0	1.79	0	0	0.96	0
C-130E	1134O	23	29	0	0	3	0	1.26	0	0	0.13	0
C-130E	1135O	6	8	0	0	3	0	1.33	0	0	0.50	0
C-141B	11FDG	23	24	0	0	11	0	1.04	0	0	0.48	0
C-141B	11HCG	28	67	0	0	32	0	2.39	0	0	1.14	0
F-16C/D	11CCA	38	96	0	0	0	50	2.53	0	0	0	1.32
F-16C/D	11CCB	22	38	0	0	0	49	1.73	0	0	0	2.23
F-16C/D	11EBL	3	2	0	0	0	0	0.67	0	0	0	0
F-15C/D	11ARE	3	7	0	0	0	1	2.33	0	0	0	0.33
F-15C/D	11ASJ	6	2	0	0	0	2	0.33	0	0	0	0.33
F-15C/D	13HAC	7	0	0	0	1	0	0	0	0	0.14	0
						Average		1.72	0.00	0.00	0.62	0.26
						Correlated		1.89	0.00	0.00	0.62	0.00

HISTORICAL K-FACTOR DATA SHEET

Equipment: PLUMBING/TUBING	Reliability Type: Mechanical	Correlation Factors	
Comments: Loose/damaged hardware.		Human-Induced:	1.10
		Environment-Induced:	0.00
		Equipment-Induced:	0.00
		False Maintenance:	1.00
		Access Maintenance:	0.00

System/ Model	WUC	Quantity of Maintenance Actions						K-Factor Element Values				
		Inherent Cause	Human-Induced	Env.-Induced	Equip.-Induced	False Maint.	Access Maint.	K1	K2	K3	K4 False	K4 Access
C-5A	45JJQ	37	9	0	0	11	0	0.24	0	0	0.30	0
C-5A	45EJU	451	118	0	0	210	0	0.26	0	0	0.47	0
C-5A	11BCM	63	6	0	0	54	0	0.10	0	0	0.86	0
C-5A	13EDB	427	73	0	0	199	0	0.17	0	0	0.47	0
C-130E	24BAP	7	0	0	0	0	0	0	0	0	0	0
C-130E	49AAM	1	0	0	0	0	0	0	0	0	0	0
C-130E	2421P	9	4	0	0	2	0	0.44	0	0	0.22	0
C-130E	12ARG	1	0	0	0	0	0	0	0	0	0	0
C-141B	23LBE	2	0	0	0	0	0	0	0	0	0	0
F-15C/D	24EAF	10	1	0	0	3	0	0.10	0	0	0.30	0
F-15C/D	24EAG	1	0	0	0	0	0	0	0	0	0	0
F-15C/D	45BAE	79	19	0	0	35	7	0.24	0	0	0.44	0.09
F-15C/D	23GBF	1	0	0	0	0	0	0	0	0	0	0
								NA	NA	NA	NA	NA
								NA	NA	NA	NA	NA
								NA	NA	NA	NA	NA
						Average		0.12	0.00	0.00	0.24	0.01
						Correlated		0.13	0.00	0.00	0.24	0.00

HISTORICAL K-FACTOR DATA SHEET

Equipment: PUMP	Reliability Type: Electro-Mechanical	Correlation Factors	
Comments: Loose/damaged hardware.		Human-Induced:	1.10
		Environment-Induced:	0.00
		Equipment-Induced:	0.00
		False Maintenance:	0.90
		Access Maintenance:	0.00

System/ Model	WUC	Quantity of Maintenance Actions						K-Factor Element Values				
		Inherent Cause	Human-Induced	Env.-Induced	Equip.-Induced	False Maint.	Access Maint.	K1	K2	K3	K4 False	K4 Access
C-5A	23UAE	37	4	0	0	14	0	0.11	0	0	0.38	0
C-5A	11LCF	12	6	0	0	2	0	0.50	0	0	0.17	0
C-5A	12BBP	3	4	0	0	0	0	1.33	0	0	0	0
C-5A	45GEO	27	7	0	0	32	0	0.26	0	0	1.19	0
C-130E	22681	53	8	0	0	17	0	0.15	0	0	0.32	0
C-130E	24111	19	2	0	0	3	0	0.11	0	0	0.16	0
C-141B	49DCY	16	2	0	0	1	0	0.13	0	0	0.06	0
C-141B	49GBM	3	0	0	0	1	0	0	0	0	0.33	0
C-141B	45BCA	11	2	0	0	17	0	0.18	0	0	1.55	0
F-16C/D	23GC	1	1	0	2	0	0	1.00	0	2.00	0	0
F-16C/D	24ADO	10	1	1	0	10	1	0.10	0.10	0	1.00	0.10
F-16C/D	24EAB	1	3	0	0	0	0	3.00	0	0	0	0
F-16C/D	46ABO	7	0	3	0	4	0	0	0.43	0	0.57	0
F-15C/D	23GBM	2	1	0	0	0	0	0.50	0	0	0	0
F-15C/D	23GCO	3	0	0	0	1	0	0	0	0	0.33	0
F-15C/D	23HAD	36	10	0	0	12	0	0.28	0	0	0.33	0
						Average		0.48	0.03	0.13	0.40	0.01
						Correlated		0.53	0.00	0.00	0.36	0.00

HISTORICAL K-FACTOR DATA SHEET

Equipment: QUICK DISCONNECT	**Reliability Type:** Mechanical	**Correlation Factors**
Comments: Loose/damaged hardware.		Human-Induced: 1.10 Environment-Induced: 0.00 Equipment-Induced: 0.00 False Maintenance: 1.00 Access Maintenance: 0.00

System/ Model	WUC	Quantity of Maintenance Actions						K-Factor Element Values				
		Inherent Cause	Human-Induced	Env.-Induced	Equip.-Induced	False Maint.	Access Maint.	K1	K2	K3	K4 False	K4 Access
C-5A	24ALK	26	8	0	0	5	0	0.31	0	0	0.19	0
C-5A	46BAY	9	1	0	0	1	0	0.11	0	0	0.11	0
C-5A	24AER	42	65	0	0	9	0	1.55	0	0	0.21	0
C-130E	452AN	35	0	0	0	12	0	0	0	0	0.34	0
C-141B	49DCZ	2	1	0	0	0	0	0.50	0	0	0	0
C-141B	45AEC	6	2	0	0	2	0	0.33	0	0	0.33	0
C-141B	45AEA	5	1	0	0	3	0	0.20	0	0	0.60	0
C-141B	45ABD	3	2	0	0	1	0	0.67	0	0	0.33	0
								NA	NA	NA	NA	NA
								NA	NA	NA	NA	NA
								NA	NA	NA	NA	NA
								NA	NA	NA	NA	NA
								NA	NA	NA	NA	NA
								NA	NA	NA	NA	NA
								NA	NA	NA	NA	NA
								NA	NA	NA	NA	NA
							Average	0.46	0.00	0.00	0.26	0.00
							Correlated	0.51	0.00	0.00	0.26	0.00

HISTORICAL K-FACTOR DATA SHEET

Equipment: BATTERY	Reliability Type: Electrical	Correlation Factors	
Comments: Loose/damaged hardware.		Human-Induced:	1.10
		Environment-Induced:	0.00
		Equipment-Induced:	0.00
		False Maintenance:	0.90
		Access Maintenance:	0.00

System/ Model	WUC	Quantity of Maintenance Actions						K-Factor Element Values				
		Inherent Cause	Human-Induced	Env.-Induced	Equip.-Induced	False Maint.	Access Maint.	K1	K2	K3	K4 False	K4 Access
C-5A	44CWC	6	0	0	0	0	0	0	0	0	0	0
C-5A	66AEC	33	1	0	0	9	0	0.03	0	0	0.27	0
C-5A	72HDO	350	34	0	0	293	0	0.10	0	0	0.84	0
C-130E	42AEO	24	18	0	0	4	0	0.75	0	0	0.17	0
C-130E	4213A	112	19	0	0	16	0	0.17	0	0	0.14	0
C-130E	44314	37	4	0	0	4	0	0.11	0	0	0.11	0
C-141B	91CAB	3	1	0	0	0	0	0.33	0	0	0	0
F-16C/D	42GAA	410	78	0	0	97	0	0.19	0	0	0.24	0
F-16C/D	42JBA	27	0	0	0	3	2	0	0	0	0.11	0.07
F-16C/D	74DGO	69	0	0	0	18	0	0	0	0	0.26	0
F-16C/D	74JEO	32	0	0	0	3	0	0	0	0	0.09	0
								NA	NA	NA	NA	NA
								NA	NA	NA	NA	NA
								NA	NA	NA	NA	NA
								NA	NA	NA	NA	NA
								NA	NA	NA	NA	NA
						Average		0.15	0.00	0.00	0.20	0.01
						Correlated		0.17	0.00	0.00	0.18	0.00

HISTORICAL K-FACTOR DATA SHEET

Equipment: BEARING/SWIVEL	Reliability Type: Mechanical	Correlation Factors	
Comments: Loose/damaged hardware.		Human-Induced:	1.10
		Environment-Induced:	0.00
		Equipment-Induced:	0.00
		False Maintenance:	1.00
		Access Maintenance:	0.00

System/ Model	WUC	Quantity of Maintenance Actions						K-Factor Element Values				
		Inherent Cause	Human-Induced	Env.-Induced	Equip.-Induced	False Maint.	Access Maint.	K1	K2	K3	K4 False	K4 Access
C-5A	23KAH	1	0	0	0	1	0	0	0	0	1.00	0
C-5A	24AGE	2	2	0	0	0	0	1.00	0	0	0	0
C-5A	11STZ	1	1	0	0	0	0	1.00	0	0	0	0
C-130E	11246	8	0	0	0	0	0	0	0	0	0	0
C-130E	22EAK	16	4	0	0	0	0	0.25	0	0	0	0
C-130E	1321D	5	0	0	0	1	0	0	0	0	0.20	0
C-130E	1131F	3	1	0	0	2	0	0.33	0	0	0.67	0
C-141B	11CEE	2	1	0	0	0	0	0.50	0	0	0	0
C-141B	14ABP	6	0	0	0	2	0	0	0	0	0.33	0
C-141B	14GBJ	19	9	0	0	5	0	0.47	0	0	0.26	0
C-141B	11HBL	4	2	0	0	3	0	0.50	0	0	0.75	0
F-16C/D	13DAC	1	0	0	0	0	0	0	0	0	0	0
F-15C/D	23ABD	1	0	0	0	1	0	0	0	0	1.00	0
F-15C/D	14EBG	18	1	0	0	10	0	0.06	0	0	0.56	0
F-15C/D	13AKC	4	2	0	0	0	0	0.50	0	0	0	0
F-15C/D	13DEE	6	0	0	0	3	0	0	0	0	0.50	0
						Average		0.29	0.00	0.00	0.33	0.00
						Correlated		0.32	0.00	0.00	0.33	0.00

Historical Data Evaluation

Data used for this study included C-5A, C-131E, C-141B, F-16C/D, and F-15C/D aircraft maintenance data. Much of the available data on these systems was utilized. Human-induced and false alarm/incorrect isolation data were used with appropriate correlation factors applied to account for the space environment and the SSF-specific design. Data which were not considered applicable to SSF included environment-induced, equipment-induced and equipment removed to access other equipment. Specific data which were omitted from the historical data included maintenance due to servicing, cannibalization, and foreign-object damage. Table D-1 presents a listing of the aircraft equipment evaluated for this study. As shown, each equipment type is identified with an associated equipment reliability type classification.

Appendix A presents the historical K-Factor data sheets for the 28 types of equipment used in this evaluation. As shown, each data sheet contains

1. The aircraft model/system
2. The aircraft equipment Work Unit Codes (WUCs)
3. The quantity of maintenance actions that occurred
4. Equipment type name
5. Reliability type classification
6. Correlation factors used to develop SSF K-Factor subelement values
7. Aircraft average K-Factor values
8. SSF correlated values
9. Comments

The maintenance action historical data was categorized based on equipment malfunction codes which are generated and used by the military aircraft industry. These codes define the specific causes for equipment maintenance.

The following background information pertains to the aircraft data sources used in this study.

C-5A: The reporting period was 04/01/85 through 03/31/87. Total flight hours accumulated in that period were 99,163.

C-130E: The reporting period was 04/01/85 through 03/31/87. Total flight hours accumulated in that period were 249,999.

C-141B: The reporting period was 04/01/85 through 03/31/87. Total flight hours accumulated in that period were 511,192.

F-16C/D: The reporting period was 07/86 through 06/87. Total flight hours accumulated in that period were 77,951.

F-15C/D: The reporting period was 07/86 through 06/87. Total flight hours accumulated in that period were 110,638.

TABLE D-1.
Historical Equipment Reliability Types

Equipment	Reliability Type					
	Mechanical	Structural	Structural-Mechanical	Electrical	Electro-Mechanical	Electronic
Actuator	X				X	
Antenna				X		
Battery				X		
Bearing Swivel	X					
Bukhead			X			
Cable/Harness				X		
Controller						X
Control Panel				X		
Databus				X		
Duct		X				
Elect. Receptacle				X		
Frame/Rack		X				
Heat Exchange Cooler	X					
Heater				X		
Hose	X					
Light				X		
Panel/Door/Cover			X			
Plumbing/Tubing	X					
Pump					X	
Quick Disconnect	X					
Structure		X				
Strut/Link/LOngeron		X				
Tank/Bottle	X					
Thermal Sheild			X			
Valve	X				X	
Window		X				

K-Factor Evaluations and Correlations

The following describes the various K-Factor subelement evaluations and correlations used in this study.

Human Error Subelement (K1). The K-Factor subelement K1 accommodates occurrences when equipment is inadvertently damaged due to misuse, improper maintenance, and incidental contact. Causes for human error include such things as visibility/perception, dexterity/mobility, comfort, fatigue, and physical orientation. Training and motivation have been noted as being contributors to human error. However, for purposes of this study, it was assumed that personnel working on Earth were equally trained and had equal motivation in performing their tasks. Only physical differences were reviewed in this correlation. The human error rates estimated for the SSF were developed using a two-step approach. The first step was to evaluate historical data pertaining to human error rates. The second step was to ascertain how the space environment (using a Shuttle space suit) was different compared to an Earth work environment. This difference created a correlation factor which was applied to the historical data to develop SSF estimates.

To accommodate human error in the space application, a correlation survey was used. Appendix B presents the survey questionnaire. In correlating the data, a range of 0 to 2 was used for the "Environment Comparison Evaluation" portion of the survey. Accordingly, if the human error element were the same for space as on the ground, the "same" category was circled and a value of 1 applied. Specific instructions for completing the survey and applicable examples are provided on the survey questionnaire sheets.

The survey was distributed to several groups of people, ranging from design and human factors engineers to astronauts with EVA experience. Responses to the survey varied; however, the unanimous opinion was that the space environment is a more difficult place in which to work. Results of the survey produced a range from a 10% increase to an 80% increase in human error potential. Upon reviewing the results, it was noted that persons with actual EVA experience considered the two environments quite similar. Typically, the design and human factor engineers were less optimistic in their opinions. Because there was such a large range of opinions, it was decided that the human error correlation factor given by EVA-experienced personnel would be used for this study. Accordingly, a 1.10 correlation factor has been used.

It can be noted that the survey was deemed somewhat vague because people have different interpretations of the human error elements. To improve consistency of the results, specific definitions should have been included in the survey instructions. Also, many responses indicated that specific maintenance tasks should have been considered to allow for a better evaluation. The purpose of the survey, however, was to evaluate maintenance activities in general.

Environment-induced Subelement (K2). The K-factor element K2 accommodates maintenance rates caused by natural environment effects. The natural environments defined in SSP 30425 and SSP 30420 were used as a basis for the environmental assessment of this study. Reliability references (MIL-HDBK-217E and Rome Air Development Center-Reliability Engineer's Tool Kit) were reviewed to determine which of the various environments were accommodated in the MTBF calculations. Results of the review indicated that environments such as oxidation, thermal, vibration, and pressure (atmospheric and vacuum) were accounted for in the MTBF predictions. However, two environments (micrometeoroid/space debris and ionizing radiation) were found as not being contained in these predictions. Accordingly, these two environments have been included in the K-Factor **K2** subelement assessment. The following section describes these two environmental factors.

Micrometeoroid and Space Debris (MMD). Micrometeoroid and space debris could have substantial impact on the Space Station if protective equipment falls short of requirements. Currently, substantial efforts are under way to assure that critical SSF equipment is protected to the level specified in the program requirements. The requirement states that the probability of no penetration (PNP) for critical equipment (assumed as Critical 1S equipment), over a 10-year period, must be .9955. A probability of no penetration of .95 for non-critical equipment (assumed as all other equipment) has been assigned for purposes of this study. Even though there are no requirements for non-critical equipment, a level of .95 appears reasonable and achievable.

The following derivation was used in determining the MTBP for these two levels of protection.

$$PNP = e^{-\lambda_{MMD} t} = e^{\frac{-t}{MTBP}} \qquad \text{(using } MTBP = \frac{1}{\lambda}\text{)}$$

Where: MTBP is defined as mean time between micrometeoroid/debris penetration of equipment, l represents the equipment penetration rate, and t represents the time to penetration. Note: the probability of no penetrations derivation is based on "Space Station Integrated Wall Design and Penetration Damage Control" final report (report number D180-30550-1) dated July 1987.

Solving for MTBP yields:

$$MTBP = \frac{-t}{\ln PNP}$$

With: t = 87,600 (hours per 10 years) and PNP = .9955 for critical equipment and .95 for non-critical equipment MTBP becomes:

MTBP = 19,422,834 (for .9955 protection level)
MTBP = 1,707,826 (for .95 protection level)

Now, to determine the mean time between maintenance actions (MTBMA) due to both MMD and inherent (INH) random causes the following equation is used.

$$MTBM_{MMD+INH} = \left[\frac{1}{MTBF} + \frac{1}{MTBP}\right]^{-1}$$

Where: MTBMA is defined as the time between maintenance actions (based in hours) resulting from both MMD and inherent causes and MTBF is the inherent time between failures.

Now to solve for the K-Factor element **K2** (for MMD causes) the equation becomes:

$$K2_{MMD} = 1 - \left[\frac{MTBF}{MTBMA_{MMD+INH}}\right]^{-1}$$

With t = 87600 the equation becomes:

$$\Rightarrow K2_{MMD} = 1 - \left[\frac{MTBF}{\left(\frac{-1}{87600} \text{ X} \ln PNP\right) + \frac{1}{MTBF}}\right]^{-1}$$

TABLE D-2
K2 Values for Micrometeoroid Environment

MTBF, hours	PNP	
	0.99550	0.95000
0 TO 10K	0.00052	0.00586
10K TO 100K	0.00515	0.05860
100K TO 1M	0.05150	0.58600
1M TO 10M	0.51500	5.86000
10M TO 100M	5.15000	58.6000

The typical MTBF range for electronic, electrical and electro-mechanical reliability equipment types is 10,000 to 100,000 hours. The MTBF range for mechanical types is 100,000 to 1,000,000 hours. To establish an overall **K2** value for each reliability equipment category, a ratio method was utilized. This ratio was used because of the fact that no particular reliability type has all critical or all non-critical equipment. The actual ratio of critical to non-critical equipment for each reliability category will be established as FMEAs are performed and CILs are developed. However, since the FMEAs are not yet complete, an engineering judgment of the ratio has been made. A 20% critical to 80% non-critical ratio has been used for purposes of this study. Using this ratio, the values shown in Table D-3 were calculated for the mechanical, electrical, electronic, and electro-mechanical equipment categories.

Ionizing Radiation (IR)

Ionizing radiation has unique effects on various categories of equipment. The IR is known to degrade seals and lubricant properties, break down bonding of composites, and cause both electron migration (over time) and single-event upsets (due to solar flares) within electronic component software programs. Because there is much statistical uncertainty associated with the IR phenomenon, the effects of IR have been estimated for each equipment category using engineering judgment. This method was used because, although some data on IR are currently available, not much has yet been quantified sufficiently to aid in the development of better estimates. It is expected, however, that with further evaluation of the Long Duration Exposure Facility (LDEF) test results, more definitive and substantiated data will become available over the next year. This assessment then can be revisited to implement the new data.

To accommodate the uncertainty, and for purposes of this study, the following IR environment values for **K2** have been used. Mechanical and electrical types of equipment have been estimated at 0.02. This is based on seal and lubricant degradation with associated contamination potentials. Structural and structural-mechanical equipment have been deemed least affected by IR. In fact, with the current SSF strut and longeron design baseline (composite structure within an aluminum layer), no appreciable IR degradation is expected for the entire 30-year life of SSF. Accordingly, structural and structural-mechani-

TABLE D-3
K2 (MMD) Values for Each Equipment Category

Type	Critical		Non-critical		Total *
	%	Table Value	%	Table Value	K2 (MMD)
Mechanical	0.20	0.05150	0.80	0.58600	0.48
Electrical	0.20	0.00515	0.80	0.05860	0.05
Electro-Mechanical	0.20	0.00515	0.80	0.05860	0.05
Electronic	0.20	0.00515	0.80	0.05860	0.05
Structural	--	--	--	--	0.00**
Structural-Mechanical	--	--	--	--	0.00**

* Rounded to the nearest two decimal places.

** It is assumed that structural and structural-mechanical equipment MTBFs are based on the environment-induced damage potential. These environmental effects are the drivers (main failure mechanism) in the inherent MTBF predictions. Accordingly, a value of 0.00 has been assigned for micrometeoroid/debris effects on these types of equipment.

cal types of equipment have been estimated at 0.00 for IR effects. Electro-mechanical types of equipment have been estimated at 0.05 based on seal and lubricant degradation with associated contamination potentials. Note that this rate is greater than the mechanical and electrical types owing mainly to the increased quantities of equipment containing seals and lubricants in this reliability-type category. Electronic types of equipment have been deemed the most susceptible to IR effects. Software programs can be adversely affected (over time) by electron migration and electrical property degradation. Also, because random single-event upsets can be caused by intense solar flares, an estimate of 0.10 has been used for electronic equipment types. The effect IR has on electronic equipment is a good subject for equipment life studies.

It can be noted that when electronic controller software has been affected, the corrective action is to reload the programming. The other equipment types will typically require replacement after sustained IR degradation.

Equipment-Induced Subelement (K3). The K-Factor element **K3** accommodates maintenance rates caused by equipment malfunctions/failures which, in turn, causes other interfacing or surrounding equipment failures. The **K3** values have been established using aircraft historical data as a basis. These data are appropriate for SSF equipment use because the design requirements are the same. Both aircraft and SSF requirements state that failures of one piece of equipment shall not cause the failure of another piece of equipment. To accommodate this fail-safe feature, shielding, partitioning, protective devices, and similar items are implemented at system and component levels. To verify the implementations, extensive analyses and testing are performed.

As shown in the various historical data sheets (reference Appendix A) the extent of equipment-induced failures has been negligible (less than 1 percent). Accordingly, it can be projected that SSF equipment will also exhibit these same characteristics. And, to accommodate a potential for any such occurrences, a value of 0.01 has been assigned for each equipment category. Note that this is the result of rounding up to the nearest two decimal places.

No-Defect Rate Element (K4). The K-Factor element **K4** accommodates maintenance rates caused by 1) false alarms/incorrect fault isolation and 2) in-the-way removals to gain access for other equipment maintenance. Each of these is considered a subelement. The false alarm and incorrect fault isolation element rate was developed using a two-step approach. The first step was to evaluate aircraft historical data pertaining to these items. The second step was to ascertain how aircraft automatic BIT design compares to the SSF equipment BIT philosophy and design. The subelement of in-the-way removals (or access-caused maintenance actions) has been estimated, based on SSF specific equipment design. This is because the SSF Program requirements state that equipment will not be removed to gain access to other equipment; whereas, based on current information, the aircraft programs reviewed in this study have no such requirement.

The following sections provide the methodology and rationale used in developing the no-defect subelement values.

False Alarm / Incorrect Fault Isolation. Automatic BIT for the SSF systems and equipment should exhibit a more reliable effectivity rate than the rates documented in the historical data sheets.

The design activity for the BIT of the most recent historical data herein is 8- to 10-year-old technology. Advancements in BIT development techniques, hardware and software technology, and improvements in requirements definition have indicated on more recent programs (programs such as the F-15E and F-18, for which limited data is available) that BIT and built-in test equipment (BITE) capabilities have experienced continued improvement. The trend, clearly, is more effective BIT results.

The use of better design techniques has improved BIT effectivity. Continuous BIT monitoring makes use of real-time, run-time operational functions for unambiguous fault detection and isolation. One function, or operation, or capability, is monitored by dedicated BIT/BITE. As this is the least complex design for BIT, there is less chance of BIT errors. When a failure is detected, BIT routines are designed to repeat before declaring a failed asset. This reduces fault declarations as a result of transients or one-time anomalies. The BIT design is now concurrent with hardware/software design, not something that is added on after prime circuitry has been developed. This allows for earlier use of BIT (i.e., in the integration labs, on the manufacturing floor, etc.) and provides for extensive debugging before BIT is deployed. Also, hardware topology has matured to the extent that certain hardware functions are implemented in similar or exactly the same manner as on other systems. For example, a digital pulse-counting circuit is the same on an amplifier as it is on a computer. Repeated use of hardware topology has allowed a maturation process of the test strategy for that hardware. Newer systems utilize "lessons learned" from older systems.

Implementation of BIT in hardware versus software has improved effectivity. The use of hybrids and gate arrays with on-board (chip level) test capability has removed many "software faults" from the list of BIT failure mechanisms. Hardware is easier to troubleshoot and maintain than software. Also, improvements in manufacturing processes for prime equipment have eliminated many failure mechanisms that were very difficult to isolate with built-in test. The use of multi-layer core boards (PWBs) and automated soldering techniques have greatly reduced ambiguous failure indications due to manufacturing flaws.

Requirements definition has evolved simultaneously with BIT design. More detailed requirements, using clearly defined capabilities with exacting parameters, have removed "interpretation" problems that generally manifest themselves in less than optimum design. BIT effectivity analysis techniques have required the efficient development of BIT.

All of the previous discussion justifies optimism in BIT capabilities. Accordingly, a decrease in maintenance actions should occur compared to aircraft historical data. The amount of decrease, due to improvements in automatic isolation, is estimated at 10%. Therefore, the correction factor for equipment which has BIT is 0.90. Equipment in this category includes electrical, electro-mechanical, and electronic equipment types. The other types of equipment (structural, structural-mechanical, and mechanical), which typically do not utilize BIT, will be subjected to manual fault isolation techniques. These techniques, along with the associated test equipment, are considered similar in both aircraft and spacecraft equipment. Therefore, the equipment which typically requires manual testing will have a correlation factor of 1.00.

In-the-Way Removals. The K-Factor **K4** subelement value for access-caused maintenance actions is dependent on specific SSF equipment design. In cases where the equipment under K-Factor evaluation also must be disturbed sometimes and/or removed to allow access for other equipment maintenance, this additional K-Factor subelement value has been developed and incorporated into the total no-defect rate element value. Also, an additional value is necessary for inclusion in that equipment's **K2** because each time a piece of equipment is handled, it has the potential for being damaged. To accommodate this, the equipment's human-error- induced damage rate is to be used. The access-caused action value is developed by determining the failure rate relative ratio of the equipment being handled to gain access to the equipment being evaluated for a K-Factor value. The additional value for human-induced is developed by multiplying the preceding ratio by the equipment's appropriate human-induced (K1) value. To illustrate this concept, observe the following example:

Example: Given a piece of equipment under K-Factor evaluation, E(1), has a failure rate of 100, and it must be removed occasionally to allow access to a failed item, E(2), with a failure rate of 10, the access ratio of 10/100 or 0.10 is produced. This ratio is then the **K4** value of the K-Factor. Now, given the item E(1) has a human-error-induced damage rate of 0.20, the additional human error value is 0.10 X 0.20 = 0.02. This 0.02 is then added to the original human error value to yield the actual rate at which the equipment will need to replaced, due to the inherent rate of contact plus the access-caused rate of contact.

Access-caused rates are typically low because of the SSF Program requirements. Accordingly, values of 0.01 have been assigned to the mechanical, structural, electrical, and electro-mechanical equipment categories. Structural-mechanical equipment has been assigned a value of 0.00 because of definition used in this study (i.e., equipment which provides protection and is typically displaced to gain access for other equipment maintenance). The electronic equipment category has the highest estimated access-caused rate. This is attributable to the fact that almost all electronic equipment is being mounted on somewhat complex cold plates. This type of mounting scheme is necessary to meet the thermal performance requirements. Since electronic box types are the largest portion of electronic configured equipment on SSF, an overall value of 0.10 is being utilized for the K4 access-caused rate.

K-Factor Summary

Table D-4, presents the equipment K-Factor summary matrix. Each equipment category (based on reliability type) is shown with its associated K-Factor subelement values and total K-Factor value.

The Fisher-Price Database contains items identified as "MAINT-TYPE" = maintenance. These entries represent life changeout, equipment cleaning (camera lens, windows, and similar items), and some in-situ repairs. Since these are considered scheduled maintenance events, to a large extent, it has been assumed that the "MTBF" listed is really a mean-time-between maintenance actions (MTBMA). Therefore, by definition, a K-Factor value of 1.00 has been applied to these items. To account for the human-error-induced damage potential which occurs during the scheduled maintenance events, the error damage rate has been included in the corrective maintenance term of the equipment. That is, the rate has been included in the K1 value term which coincides with the inherent (random) failure expression in the database.

TABLE D-4
Equipment K-Factor Summary Matrix

Equipment Reliability Type	Human-Error-Induced Rate (K1)	Environnment-Induced Rate (K2)	Equipment-Induced Rate (K3)	No-Deffect Rate (K4)		Total K-Factor Value
				False/ Incorrect Maintenance Rate	Access-Caused Rate	
Mechanical	0.31	0.50	0.01	0.32	0.01	2.15
Structural	0.46	0.00	0.01	0.26	0.01	1.74
Structural-Mechanical	1.76	0.00	0.01	0.34	0.00	3.11
Electrical	0.19	0.07	0.01	0.23	0.01	1.51
Electro-Mechanical	0.34	0.10	0.01	0.36	0.01	1.82
Electronic	0.12	0.15	0.01	0.41	0.10	1.79

* Based on Use of K-Factor Equation

Results and Conclusions

The following results and conclusions can be made, based on the findings of this study:

1. K-Factor is shown to be a substantial factor when considering total maintenance demands. Human-induced maintenance rates and false maintenance rates have historically been shown as the major drivers. The methodology used to develop the equipment type K-Factor values was based on a solid approach. The methodology allows future equipment K-Factor assignments to be made with minimum effort and provides reasonably good results. It can be stated with a high level of confidence that if the K-Factor evaluations were performed down to a specific equipment level (i.e., a unique K-Factor value for an antenna, valve, heat exchanger, cable, etc.), the overall results would not change more than a few percent.

2. As demonstrated in the K-Factor summary section of this report, certain equipment types exhibited large K-Factor subelement values. These "heavy hitters" are summarized as follows:

   A. Structural-mechanical equipment exhibits a high human-induced damage rate.

   B. Mechanical equipment exhibits a high environment-induced damage rate.

   C. Electronic equipment exhibits high environmental and no-defect removal rates.

3. The total K-Factor value (for the various equipment type category) ranged from 1.51 to 3.11. This range is consistent with what has been repeatedly verified on major programs in which maintenance data have been tracked. Also noted was the fact that there was a minimal variation between the values of specific equipment types within a given category. The standard deviations of equipment values within each category were all around 0.2. This demonstrated appropriate equipment selections in each of the equipment category groupings.

4. The amount of unmanned and manned spacecraft experience data were found to be negligible and/or not readily quantifiable. Some equipment-induced and environment-induced data exist, but not enough to provide useful correlations. Environmental data are currently being quantified via LDEF studies, but, were not available at the time of this study. Shuttle data indicated that equipment-induced occurrences do exist; however, they are sparse and sporadic. Accordingly, it was decided to use a Space Station-specific equipment design approach and provisions to estimate the equipment-induced rate.

5. During the course of this study, it was acknowledged that equipment location could potentially drive the K-Factor to different values. The difference would be mainly attributable to human and environmental effects. However, upon further evaluation the differences appear negligible compared to the current K-Factor values. The rationale for not distinguishing and using equipment location effects is as follows:

   A. Human-induced causes are already included in most of the equipment types (i.e., control panels, covers, doors, etc.) which have moderate human contact over time. These types of equipment are inherently exposed to human interface and, therefore, do not need to be increased to account for a greater damage potential.

   B. Environmental effects between the zenith, nadar, and velocity vector orientations will be somewhat different. However, considering that for every piece of equipment with greater exposure, there is another piece of equipment with less exposure, an average rate appears applicable. Also, because of the current SSF equipment protection design approach (utilizing appropriate shielding), equipment located predominantly in more vulnerable locations is being designed for greater protection to achieve the required probability of no penetration.

6. The method being used to consider access-caused maintenance actions is appropriate for use at this stage of SSF development and produces reasonable results. However, a more accurate method in estimating the EVA demand, in which the in-the-way removal time is added to the mean-time-to-repair (MTTR) of the ORU being serviced, can be used at a later date. This other method inherently yields better estimates because MTTRs are developed on a specific equipment case-by-case basis; whereas, the K-Factor is being developed for more generalized equipment categories. If MTTR is used at a later date, then the K4 value for access-caused maintenance actions can be omitted. However, the portion accounting for equipment damage due to human error would remain, regardless of which method was used.

Recommendations

The following recommendations are made based on the results of this study.

1. Results of this study should be used to provide design direction for various SSF equipment. If emphasis is applied on the items driving K-Factor values, reduced EVA demand will result. A prime example would be to ruggedize access covers, panels, mounting guides, and connecting fasteners to reduce human-induced damages of the fastening mechanisms and attaching hardware. This should be considered necessary because, historically, damage rates for similar types of equipment are shown to be a major factor in causing additional maintenance actions. Accordingly, establish and quantify test requirements for the program.

2. A detailed study of human error correlations should be performed to gain better understanding of drivers which cause humans to err in the space environment. Once the drivers are singled out, design efforts should be made to accommodate and reduce the causes. A detailed study is recommended because human-error-induced rates are a significant portion of the overall K-Factor totals.

3. With the appreciable affects of ionizing radiation on electronic equipment, and because SSF has many electronic devices located in the external environment, stringent equipment radiation hardening specifications/processes should be considered.

4. As analyses (such as the FMEAs and CILs) are completed, the ratio (20% critical items to 80% non-critical items) used in developing the environment-induced K-Factor subelement values should be revisited. This is needed because the ratio turns out to be a driving element in the value development. Also, consider requirements for non-critical equipment (e.g., 95% for critical 1R, etc.)

5. Assure that SSF Program has an effective tracking program and database so that future manned space programs will have quantifiable and traceable maintenance information for use in estimating resource demands. This data will also provide for monitoring SSF Program trends and allow personnel to be alerted to any developing adverse trend conditions. Establish possible "alarm levels" beyond which corrective action/investigation would be required.

Acknowledgments

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Bibliography

Supporting Data Sources

The following presents the supporting data accumulated from various sources other than the military aircraft maintenance databases. These findings were used as supplemental information and in some cases provided a basis for the K-Factor approach and values.

1. **Long Duration Exposure Facility**:
   - Martin Marietta inspection trip report
   - NASA News (release 90-23)

   Data Remarks:
   - Long-term environmental effects of spaceflight on a broad range of materials and components.
   - Nearly half of all spacecraft failure causes are unknown.
   - Effects of exposure of bombardment by micrometeoroids and orbital debris, atomic oxygen impingement, ultraviolet (and other radiation effects) and.unknowns are under current evaluation.
2. **Rome Air Development Center**:
   - RADC Reliability Engineer's Tool Kit
     Data Remarks:
   - (Table A6-1) Provides basis for K-Factor element categorizations. Defines K-Factor element applicability when using existing reliability data.
   - (Table A11-2) Provides environment conversions from military to space applications.

   Basis of conversions due to environmental stresses (except ionizing radiation). Does not account for micrometeoroid environment.
3. **R&M Symposium**:
   - "An inside view of Air Force ground electronic equipment maintenance"
     Data Remarks:
   - Provides maintenance (human)-induced impact on maintenance activities.
   - 14 USAF bases evaluated.
   - Consensus figure (weighted summary) of 21.8% of activities due to maintenance impacts.

4. **MIL-HDBK-217E**:

Data Remarks:

- Provides descriptions and categories of environmental elements.
- NOTE: Data provided is related to the MTBF (random failure causes)

5. **Skylab**:

- Data experience Bulletin No. 26
- Systems chronological performance evaluation study (final report)

  Data Remarks:

- Provides qualitative and quantitative data on environment impacts to various types of equipment

6. **National Space Transportation System**:

- Problem and Corrective Action System

  Data Remarks:

- Orbiter in-flight failure data were evaluated as part of this study. However, because the data were not well quantified (in terms of time dependencies and MTBFs), it could not be used as a basis in developing K-Factor values.

Appendix D

Attachment 1 - Historical K-Factor Data Sheets

HISTORICAL K-FACTOR DATA SHEET

Equipment: ACTUATOR	**Reliability Type:** Mechanical	**Correlation Factors**
Comments: Loose/damaged hardware.		Human-Induced: 1.10 Environment-Induced: 0.00 Equipment-Induced: 0.00 False Maintenance: 1.00 Access Maintenance: 0.00

System/ Model	WUC	Quantity of Maintenance Actions						K-Factor Element Values				
		Inherent Cause	Human-Induced	Env.-Induced	Equip.-Induced	False Maint.	Access Maint.	K1	K2	K3	K4 False	K4 Access
C-5A	14YZV	3	2	0	0	0	0	0.67	0	0	0	0
C-5A	14ZAV	2	0	0	0	0	0	0	0	0	0	0
C-5A	14YYB	6	2	0	0	0	0	0.33	0	0	0	0
C-130E	1129H	108	9	0	0	3	0	0.08	0	0	0.03	0
C-130E	14341	20	2	0	0	2	0	0.10	0	0	0.10	0
C-141B	11DBA	12	1	0	0	4	0	0.08	0	0	0.33	0
F-16C/D	13BCF	55	9	2	0	1	2	0.16	0.04	0	0.02	0.04
F-16C/D	13CBB	83	11	2	0	2	2	0.13	0.02	0	0.02	0.02
F-16C/D	13CBD	157	17	4	0	5	0	0.11	0.03	0	0.03	0
F-16C/D	14BAB	5	0	0	0	2	0	0	0	0	0.40	0
F-16C/D	14DEO	2	5	1	0	0	0	2.50	0.50	0	0	0
F-15C/D	13ACO	14	7	0	0	8	4	0.50	0	0	0.57	0.29
F-15C/D	13BCO	8	2	0	0	4	0	0.25	0	0	0.50	0
F-15C/D	13BDA	3	2	0	0	3	0	0.67	0	0	1.00	0
F-15C/D	13BEC	31	0	0	0	6	2	0	0	0	0.19	0.06
F-15C/D	13BEX	1	0	0	0	0	0	0	0	0	0	0
						Average		0.35	0.04	0.00	0.20	0.03
						Correlated		0.39	0.00	0.00	0.20	0.00

HISTORICAL K-FACTOR DATA SHEET

Equipment: ACTUATOR	Reliability Type: Electro-Mechanical	Correlation Factors	
Comments: Loose/damaged hardware.		Human-Induced:	1.10
		Environment-Induced:	0.00
		Equipment-Induced:	0.00
		False Maintenance:	0.90
		Access Maintenance:	0.00

System/ Model	WUC	Quantity of Maintenance Actions						K-Factor Element Values				
		Inherent Cause	Human-Induced	Env.-Induced	Equip.-Induced	False Maint.	Access Maint.	K1	K2	K3	K4 False	K4 Access
C-5A	11GEB	105	18	0	0	33	0	0.17	0	0	0.31	0
C-5A	24AFB	2	2	0	0	1	0	1.00	0	0	0.50	0
C-5A	14NFK	3	3	0	0	1	0	1.00	0	0	0.33	0
C-5A	13BEP	11	3	0	0	4	0	0.27	0	0	0.36	0
C-5A	12DCU	5	2	0	0	2	0	0.40	0	0	0.40	0
C-130E	1424C	4	1	0	0	2	0	0.25	0	0	0.50	0
C-130E	2414E	49	18	0	0	14	0	0.37	0	0	0.29	0
C-141B	23LRF	14	1	0	0	2	0	0.07	0	0	0.14	0
C-141B	23LAG	153	15	0	0	18	0	0.10	0	0	0.12	0
C-141B	14FAM	94	4	0	0	32	0	0.04	0	0	0.34	0
F-16C/D	12CCA	85	0	0	0	50	10	0	0	0	0.59	0.12
F-16C/D	12CCB	19	0	0	0	7	1	0	0	0	0.37	0.05
F-16C/D	12EAB	5	0	0	1	2	0	0	0	0.20	0.40	0
F-16C/D	14BAB	5	0	0	0	2	0	0	0	0	0.40	0
F-15C/D	12EAA	51	0	0	0	29	8	0	0	0	0.57	0.16
F-15C/D	13CCE	4	0	0	0	1	0	0	0	0	0.25	0
						Average		0.23	0.00	0.01	0.37	0.02
						Correlated		0.25	0.00	0.00	0.33	0.00

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Filename: ACTUATOR2

HISTORICAL K-FACTOR DATA SHEET

Equipment: ANTENNA

Reliability Type: Electrical

Comments: Loose/damaged hardware.

Correlation Factors

Human-Induced:	1.10
Environment-Induced:	0.00
Equipment-Induced:	0.00
False Maintenance:	0.90
Access Maintenance:	0.00

System/ Model	WUC	Quantity of Maintenance Actions						K-Factor Element Values				
		Inherent Cause	Human-Induced	Env.-Induced	Equip.-Induced	False Maint.	Access Maint.	K1	K2	K3	K4 False	K4 Access
C-5A	72GCB	14	0	0	0	9	0	0	0	0	0.64	0
C-5A	61AGA	32	3	0	0	9	0	0.09	0	0	0.28	0
C-5A	71ECE	15	0	0	0	0	0	0	0	0	0	0
C-5A	71JCB	13	2	0	0	0	0	0.15	0	0	0	0
C-5A	72ACO	44	3	0	0	24	0	0.07	0	0	0.55	0
C-130E	61148	5	1	0	0	1	0	0.20	0	0	0.20	0
C-130E	71ZFO	39	11	0	0	5	0	0.28	0	0	0.13	0
C-141B	62AAA	10	2	0	0	11	0	0.20	0	0	1.10	0
C-141B	62BAA	29	3	0	0	17	0	0.10	0	0	0.59	0
C-141B	66CAB	15	4	0	0	2	0	0.27	0	0	0.13	0
C-141B	71DAA	17	15	0	0	4	0	0.88	0	0	0.24	0
F-16C/D	74LDO	2	0	0	0	0	0	0	0	0	0	0
F-16C/D	74AMO	89	16	0	0	21	14	0.18	0	0	0.24	0.16
F-16C/D	62CBO	3	0	0	0	0	0	0	0	0	0	0
F-16C/D	63BEO	16	1	0	0	3	0	0.06	0	0	0.19	0
F-15C/D	63ADO	143	29	0	0	15	0	0.20	0	0	0.10	0
						Average		0.17	0.00	0.00	0.28	0.01
						Correlated		0.19	0.00	0.00	0.25	0.00

HISTORICAL K-FACTOR DATA SHEET

Equipment: STRUCTURE	Reliability Type: Structural	Correlation Factors	
Comments: Loose/damaged hardware.		Human-Induced:	1.10
		Environment-Induced:	0.00
		Equipment-Induced:	0.00
		False Maintenance:	1.00
		Access Maintenance:	0.00

System/ Model	WUC	Quantity of Maintenance Actions						K-Factor Element Values				
		Inherent Cause	Human-Induced	Env.-Induced	Equip.-Induced	False Maint.	Access Maint.	K1	K2	K3	K4 False	K4 Access
C-5A	11SCC	26	5	0	0	3	0	0.19	0	0	0.12	0
C-5A	11SJE	41	0	0	0	0	0	0	0	0	0	0
C-5A	11SLE	9	2	0	0	1	0	0.22	0	0	0.11	0
C-5A	11TUE	256	230	0	0	25	0	0.90	0	0	0.10	0
C-5A	11TUF	168	176	0	0	38	0	1.05	0	0	0.23	0
C-130E	11412	16	12	0	0	1	0	0.75	0	0	0.06	0
C-130E	11422	27	15	0	0	1	0	0.56	0	0	0.04	0
C-130E	11432	21	16	0	0	9	0	0.76	0	0	0.43	0
F-16C/D	11EAB	2	2	0	0	0	0	1.00	0	0	0	0
F-16C/D	11EAL	10	1	0	0	0	0	0.10	0	0	0	0
F-16C/D	11GOO	2	2	0	0	1	0	1.00	0	0	0.50	0
F-15C/D	11AFO	32	5	0	0	23	0	0.16	0	0	0.72	0
F-15C/D	11AHF	3	3	0	0	1	0	1.00	0	0	0.33	0
F-15C/D	11ARN	7	5	0	0	2	3	0.71	0	0	0.29	0.43
F-15C/D	11AOO	274	245	0	0	86	30	0.89	0	0	0.31	0.11
F-15C/D	11DOO	60	29	0	0	5	2	0.48	0	0	0.08	0.03
						Average		0.61	0.00	0.00	0.21	0.04
						Correlated		0.67	0.00	0.00	0.21	0.00

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Filename: STRUCTURE

HISTORICAL K-FACTOR DATA SHEET

Equipment: STRUT/LINK/LONGERON	Reliability Type: Structural	Correlation Factors	
Comments: Loose/damaged hardware.		Human-Induced:	1.10
		Environment-Induced:	0.00
		Equipment-Induced:	0.00
		False Maintenance:	1.00
		Access Maintenance:	0.00

System/ Model	WUC	Quantity of Maintenance Actions						K-Factor Element Values				
		Inherent Cause	Human-Induced	Env.-Induced	Equip.-Induced	False Maint.	Access Maint.	K1	K2	K3	K4 False	K4 Access
C-5A	11DAJ	2	1	0	0	0	0	0.50	0	0	0	0
C-5A	11HAL	12	3	0	0	3	0	0.25	0	0	0.25	0
C-5A	11KBH	4	0	0	0	1	0	0	0	0	0.25	0
C-5A	11SCB	12	1	0	0	0	0	0.08	0	0	0	0
C-5A	11SGB	8	0	0	0	1	0	0	0	0	0.13	0
C-130E	4112E	21	6	0	0	1	0	0.29	0	0	0.05	0
C-130E	1143L	68	21	0	0	8	0	0.31	0	0	0.12	0
C-130E	13211	51	4	0	0	37	0	0.08	0	0	0.73	0
C-141B	23TQE	12	5	0	0	1	0	0.42	0	0	0.08	0
C-141B	13BAA	38	16	0	0	28	0	0.42	0	0	0.74	0
F-16C/D	11AAE	1	0	0	0	0	0	0	0	0	0	0
F-16C/D	11GAE	1	0	0	0	0	0	0	0	0	0	0
F-16C/D	13BBA	72	29	0	0	0	0	0.40	0	0	0	0
F-15C/D	11AFO	32	5	0	0	0	0	0.16	0	0	0	0
F-15C/D	11AJA	17	2	0	0	0	2	0.12	0	0	0	0.12
F-15C/D	14CCO	26	10	0	0	0	2	0.38	0	0	0	0.08
						Average		0.21	0.00	0.00	0.15	0.01
						Correlated		0.23	0.00	0.00	0.15	0.00

HISTORICAL K-FACTOR DATA SHEET

Equipment:	Reliability Type:	Correlation Factors	
TANK/BOTTLE	Mechanical	Human-Induced:	1.10
Comments: Loose/damaged hardware.		Environment-Induced:	0.00
		Equipment-Induced:	0.00
		False Maintenance:	1.00
		Access Maintenance:	0.00

System/ Model	WUC	Quantity of Maintenance Actions						K-Factor Element Values				
		Inherent Cause	Human-Induced	Env.-Induced	Equip.-Induced	False Maint.	Access Maint.	K1	K2	K3	K4 False	K4 Access
C-5A	45LES	5	1	0	0	1	0	0.20	0	0	0.20	0
C-5A	12DAV	39	15	0	0	3	0	0.38	0	0	0.08	0
C-130E	46100	57	1	0	0	26	0	0.02	0	0	0.46	0
C-130E	22153	4	0	0	0	2	0	0	0	0	0.50	0
C-141B	46AAL	597	3	0	0	88	0	0.01	0	0	0.15	0
C-141B	46AAM	214	3	0	0	42	0	0.01	0	0	0.20	0
C-141B	46AAN	332	4	0	0	61	0	0.01	0	0	0.18	0
C-141B	46AAJ	203	6	0	0	33	0	0.03	0	0	0.16	0
F-16C/D	46DAO	46	2	2	0	29	0	0.04	0.04	0	0.63	0
F-16C/D	46DEO	68	0	11	0	40	3	0	0.16	0	0.59	0.04
F-16C/D	46FAO	22	0	0	1	11	5	0	0	0.05	0.50	0.23
F-16C/D	45AGO	76	5	1	0	8	2	0.07	0.01	0	0.11	0.03
F-16C/D	45AHO	47	14	0	0	9	2	0.30	0	0	0.19	0.04
F-16C/D	46DFO	11	0	0	0	1	0	0	0	0	0.09	0
F-15C/D	13EAH	1	0	0	0	0	0	0	0	0	0	0
F-15C/D	24DAN	1	0	0	0	0	0	0	0	0	0	0
						Average		0.07	0.01	0.00	0.25	0.02
						Correlated		0.08	0.00	0.00	0.25	0.00

HISTORICAL K-FACTOR DATA SHEET

Equipment: THERMAL SHIELD	Reliability Type: Structural/Mechanical	Correlation Factors	
Comments: Loose/damaged hardware.		Human-Induced:	1.10
		Environment-Induced:	0.00
		Equipment-Induced:	0.00
		False Maintenance:	1.00
		Access Maintenance:	0.00

System/ Model	WUC	Quantity of Maintenance Actions						K-Factor Element Values				
		Inherent Cause	Human-Induced	Env.-Induced	Equip.-Induced	False Maint.	Access Maint.	K1	K2	K3	K4 False	K4 Access
C-5A	23QGL	1	1	0	0	0	0	1.00	0	0	0	0
C-5A	23NAL	1	3	0	0	1	0	3.00	0	0	1.00	0
C-5A	23EBR	76	75	0	0	19	0	0.99	0	0	0.25	0
C-130E	1151V	65	56	0	0	33	0	0.86	0	0	0.51	0
C-141B	23PQG	25	52	0	0	2	0	2.08	0	0	0.08	0
F-16C/D	13DAF	20	13	0	0	0	0	0.65	0	0	0	0
								NA	NA	NA	NA	NA
								NA	NA	NA	NA	NA
								NA	NA	NA	NA	NA
								NA	NA	NA	NA	NA
								NA	NA	NA	NA	NA
								NA	NA	NA	NA	NA
								NA	NA	NA	NA	NA
								NA	NA	NA	NA	NA
								NA	NA	NA	NA	NA
								NA	NA	NA	NA	NA
						Average		1.43	0.00	0.00	0.31	0.00
						Correlated		1.57	0.00	0.00	0.31	0.00

HISTORICAL K-FACTOR DATA SHEET

Equipment: VALVE	**Reliability Type:** Mechanical	**Correlation Factors**
Comments: Loose/damaged hardware.		Human-Induced: 1.10 Environment-Induced: 0.00 Equipment-Induced: 0.00 False Maintenance: 1.00 Access Maintenance: 0.00

System/ Model	WUC	Quantity of Maintenance Actions						K-Factor Element Values				
		Inherent Cause	Human-Induced	Env.-Induced	Equip.-Induced	False Maint.	Access Maint.	K1	K2	K3	K4 False	K4 Access
C-5A	23ZEN	2	1	0	0	1	0	0.50	0	0	0.50	0
C-5A	41AVB	4	2	0	0	3	0	0.50	0	0	0.75	0
C-5A	47ACE	2	1	0	0	1	0	0.50	0	0	0.50	0
C-130E	46414	12	0	0	0	2	0	0	0	0	0.17	0
C-130E	452AA	35	4	0	0	16	0	0.11	0	0	0.46	0
C-130E	22AAD	8	3	0	0	3	0	0.38	0	0	0.38	0
C-141B	41ABF	3	1	0	0	1	0	0.33	0	0	0.33	0
C-141B	41ABG	1	1	0	0	1	0	1.00	0	0	1.00	0
C-141B	41DBB	5	2	0	0	2	0	0.40	0	0	0.40	0
F-16C/D	23PAC	5	0	0	0	1	1	0	0	0	0.20	0.20
F-16C/D	24DDL	2	0	0	0	1	0	0	0	0	0.50	0
F-16C/D	24DDQ	2	0	0	0	1	1	0	0	0	0.50	0.50
F-16C/D	24DGA	2	0	0	0	1	0	0	0	0	0.50	0
F-16C/D	14AEH	2	0	0	0	1	0	0	0	0	0.50	0
F-16C/D	45AED	1	1	0	0	2	0	1.00	0	0	2.00	0
F-15C/D	41ABQ	29	4	0	0	4	0	0.14	0	0	0.14	0
						Average		0.30	0.00	0.00	0.55	0.04
						Correlated		0.33	0.00	0.00	0.55	0.00

HISTORICAL K-FACTOR DATA SHEET

Equipment: VALVE	Reliability Type: Electro-Mechanical	Correlation Factors	
Comments: Loose/damaged hardware.		Human-Induced:	1.10
		Environment-Induced:	0.00
		Equipment-Induced:	0.00
		False Maintenance:	0.90
		Access Maintenance:	0.00

System/ Model	WUC	Quantity of Maintenance Actions						K-Factor Element Values				
		Inherent Cause	Human-Induced	Env.-Induced	Equip.-Induced	False Maint.	Access Maint.	K1	K2	K3	K4 False	K4 Access
C-5A	14AJN	8	0	0	0	1	0	0	0	0	0.13	0
C-5A	13ARR	7	0	0	0	4	0	0	0	0	0.57	0
C-5A	45JJG	3	1	0	0	0	0	0.33	0	0	0	0
C-5A	11BCD	8	3	0	0	5	0	0.38	0	0	0.63	0
C-5A	49BAS	38	23	0	0	20	0	0.61	0	0	0.53	0
C-130E	22AAM	22	10	0	0	6	0	0.45	0	0	0.27	0
C-130E	2264F	3	2	0	0	1	0	0.67	0	0	0.33	0
C-130E	22FAD	73	21	0	0	19	0	0.29	0	0	0.26	0
F-16C/D	13ABB	7	0	0	0	1	0	0	0	0	0.14	0
F-16C/D	13CBF	3	1	0	0	0	0	0.33	0	0	0	0
F-16C/D	13EAA	47	11	0	0	26	0	0.23	0	0	0.55	0
F-16C/D	46AAO	2	0	1	0	4	0	0	0.50	0	2.00	0
F-15C/D	12CBB	40	2	0	0	8	1	0.05	0	0	0.20	0.03
F-15C/D	13FBA	12	1	0	0	0	0	0.08	0	0	0	0
F-15C/D	14CDB	7	2	0	0	5	0	0.29	0	0	0.71	0
F-15C/D	14EBA	19	1	0	0	9	0	0.05	0	0	0.47	0
						Average		0.23	0.03	0.00	0.42	0.00
						Correlated		0.25	0.00	0.00	0.38	0.00

HISTORICAL K-FACTOR DATA SHEET

Equipment: STRUCTURE	Reliability Type: Structural	Correlation Factors	
Comments: Loose/damaged hardware.		Human-Induced:	1.10
		Environment-Induced:	0.00
		Equipment-Induced:	0.00
		False Maintenance:	1.00
		Access Maintenance:	0.00

System/ Model	WUC	Quantity of Maintenance Actions						K-Factor Element Values				
		Inherent Cause	Human-Induced	Env.-Induced	Equip.-Induced	False Maint.	Access Maint.	K1	K2	K3	K4 False	K4 Access
C-5A	11SCC	26	5	0	0	3	0	0.19	0	0	0.12	0
C-5A	11SJE	41	0	0	0	0	0	0	0	0	0	0
C-5A	11SLE	9	2	0	0	1	0	0.22	0	0	0.11	0
C-5A	11TUE	256	230	0	0	25	0	0.90	0	0	0.10	0
C-5A	11TUF	168	176	0	0	38	0	1.05	0	0	0.23	0
C-130E	11412	16	12	0	0	1	0	0.75	0	0	0.06	0
C-130E	11422	27	15	0	0	1	0	0.56	0	0	0.04	0
C-130E	11432	21	16	0	0	9	0	0.76	0	0	0.43	0
F-16C/D	11EAB	2	2	0	0	0	0	1.00	0	0	0	0
F-16C/D	11EAL	10	1	0	0	0	0	0.10	0	0	0	0
F-16C/D	11GOO	2	2	0	0	1	0	1.00	0	0	0.50	0
F-15C/D	11AFO	32	5	0	0	23	0	0.16	0	0	0.72	0
F-15C/D	11AHF	3	3	0	0	1	0	1.00	0	0	0.33	0
F-15C/D	11ARN	7	5	0	0	2	3	0.71	0	0	0.29	0.43
F-15C/D	11AOO	274	245	0	0	86	30	0.89	0	0	0.31	0.11
F-15C/D	11DOO	60	29	0	0	5	2	0.48	0	0	0.08	0.03
						Average		0.61	0.00	0.00	0.21	0.04
						Correlated		0.67	0.00	0.00	0.21	0.00

7/5/90

Filename: STRUCTURE

Appendix D

Attachment 2 - Human Error Correlation Survey

The following survey has been created to estimate a correlation in human error between ground and space environments. The objective of this survey is to better understand how space conditions may affect human performance (related to causing human errors) when working on and around SSF equipment. The intent is to provide quantitative correlations between ground and space environments. This survey specifically applies to the EVA work environment. Accordingly, a comparison is being made between working in the Earth environment to working EVA in a space suit.

For background knowledge purposes, it is requested that respondents indicate the basis of their information. If you have direct EVA experience, flight crew experience, engineering study data, or you are using personal judgment, it would be helpful to know. There are no right or wrong answers to this survey. All that is sought is your opinion based on your life experiences. It is important to remember that any and all information obtained will be kept confidential, and only group results will be released.

The survey is divided into two separate evaluations. The first is an environment comparison evaluation. The other is a human-error-element weighting evaluation. Instructions, applicable examples, and the evaluation forms are provided on the following sheets.

Please complete the survey and return by May 23, 1990. Your assistance in this matter is greatly appreciated.

Environment Comparison Evaluation:

Review each element (identified in Table B-1) which can contribute in producing human errors and estimate how that element differs from ground and space environments. Base each element estimate on the criteria shown in the table. For consistency in interpretation, the following question should be asked for the element under review. *How much does the element contribute to human error in the space environment compared to that of the ground environment?* Please perform the element evaluations by circling the applicable response for each. Also, if you have any relative comments pertaining to a particular response, please include them in in the space provided on this form. The following example demonstrates this concept.

Example: If you believe that visibility/perception contributes *more* to human error in the space environment than on the ground, circle the "M" in the table.

Attachment 2

Table 1. Environment Comparison Evaluation

Human Error Element	Much Less	Less	Same	More	Much More
Visibility/Perception ML	L	S	M	MM	
Mobility/Dexterity ML	L	S	M	MM	
Comfort	ML	L	S	M	MM
Fatigue	ML	L	S	M	MM
Orientation	ML	L	S	M	MM

Your Evaluation Basis:

Comments:

Element Weighting Evaluation. Review each human error element and assign a weighting (percentage) estimate to each according to how much each contributes to the total human error potential. Please provide a percentage for each element (as identified in Table B-2). Note that the sum of all percentages should equal 100%. The following example is provided to demonstrate the weighting evaluation concept.

Example:	Visibility/Perception	20 %
	Mobility/Dexterity	20 %
	Comfort	10 %
	Fatigue	30 %
	Orientation	20 %
		.100 %

TABLE B-2. Element Weighting Evaluation

Human Error Element	Weighting (%)
Visibility/Perception	%
Mobility/Dexterity	%
Comfort	%
Fatigue	%
Orientation	%
	100%

Comments:

Inspection Requirements and Implementation Alternatives

Appendix E

July 1990

Inspection Requirements and Implementation Alternatives

Abstract

The Space Station Freedom (SSF) design includes about 4605 structural and structural mechanical members that should be inspected on a periodic basis to determine the effects of collisions with orbital debris and micrometeoroids. While the expected frequency of significant damage is very low, the consequences of such damage to the structural integrity of the Space Station is severe enough to warrant inspection of all the passive structure on a periodic basis. The frequency of these inspections is still being determined, but there is no doubt that inspections will have to be made. Because of the scope and repetitious nature of these inspections, it is recommended that a combination of truss cameras and robots be used to scan the structure and that EVA inspection, in general, be done only by opportunity or as afforded during EVAs dedicated to ORU replacement tasks.

Introduction

Spacecraft system functionality can be determined either by active instrumentation within the system or by external observation, i.e., inspection, of the system. A combination of both instrumentation and inspection, when available, is often done and offers the obvious advantage of cross-checking the data provided by both techniques.

Active instrumentation requires sensors, electronic conditioning of the sensed signals, and routing these signals through a data system for a decision process by the flight crew or automatic circuits. Typical decisions made based on this kind of information include continuation of nominal operation of the system, moding to a different level of performance, invocation of a greater level of automatic analysis of the instrumentation data, or taking the system offline in an orderly or an emergency manner.

Active systems such as electronic, electrical, electromechanical, and fluid systems offer rich opportunity for powerful instrumentation at a modest design cost. A moderate number of temperature, pressure, linear and angular motion sensors can be strategically located to provide data which, either by direct isolation or by simple inference, can be used to indicate the state of these systems.

Passive systems such as structure can also be instrumented with sensors such as strain gauges and accelerometers to provide loading and cyclic motion data of the systems. Such instrumentation is customarily used in the engineering test and analysis during preflight development and qualification to assure that dynamic loading and deformation requirements are met by the structural design. However, a large number of these sensors are required for this process, and to include such a magnitude of sensors in the flight systems becomes problematical from a cost and reliability point of view.

The Extent of SSF Passive Structure

For SSF, there are 4605 ORUs that are passive components. These passive ORUs can be designed for long lifetime, and their associated failure rates can be expected to be very low compared to the failure rates of the active ORUs. However, the low-Earth-orbit environment includes micrometeoroids and orbital debris that will strike the Space Station with a low, but regular, frequency. Debris shields will protect the pressurized volumes, but the truss and other structure will be unshielded. The truss members have been designed such that the micrometeoroids are not expected to cause enough damage to compromise the load-bearing capability of the truss. However, larger particles such as orbital debris, though few in number, can cause structural damage that will require occasional replacement of truss members. Other structural members will also receive debris hits. From a maintenance viewpoint, these structural replacement tasks, being few in number, are not a significant contributor to the overall maintenance requirements. However, the process required to identify those few failed members out of the population of 4605 passive implies a significant amount of inspection.

Inspection Requirements

The current SSF design includes eight truss-mounted closed circuit television cameras that will be capable of viewing much of the structure. The SSF robots will have an additional 12 television cameras among them that can be moved throughout the Space Station. The SSF truss ORUs are five-meter tubes that require three viewings at 120-degree increments around the cylindrical shape in order to get a thorough inspection. For 680 truss members, this equates to 10,200 meters of linear scanning distance. At a scanning rate of 0.03 meters per second, this requires about 100 hours to inspect the entire SSF truss. The frequency at which such an inspection should occur is yet to be determined formally, but it appears prudent that early in the life of the Space Station, such an inspection should be performed annually. Thereafter, inspections might well be performed at a lower frequency of once every three years.

Inspection Implementation Alternatives

Inspection on a long and recurring basis is very boring work which is best left to machines if at all possible. The astronauts will always be on the lookout for damaged structure whenever they are on EVA, but the the amount of crew time that would be required to inspect 4605 structural members could be better spent in a more productive activity.

For a regular and complete structural inspection, television scanning appears to offer the advantage of precise and repeatable placement of cameras that can be monitored real-time onboard or on the ground and can be recorded for detailed analysis by humans or machine-image processing.

Recommendation

All extension surface inspections should be performed through an optimized combination of truss-mounted closed circuit television cameras, the SSF robot cameras, and the use of the SSF robots to position any additional inspection sensors identified in the future.

EVA Overhead

Appendix F

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July 1990

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Appendix F

Acronym List

CETA -	Crew and Equipment Translation Aid
CSA -	Canadian Space Agency
EMU -	Extravehicular Mobility Unit
ESE&T -	External Support Equipment & Tools
EVA -	Extravehicular Activity
IP -	International Partners
ITA -	Integrated Truss Assembly
IVA	Intravehicular Activity
JSC -	Johnson Space Center
MBS -	Mobile Base System
MFR -	Mobile Foot Restraint
MOD -	Mission Operations Directorate
MTTR -	Mean Time to Repair
MWS -	Mini-Work Station
ORU -	Orbital Replaceable Unit
PDR -	Preliminary Design Review
PFR -	Portable Foot Restraint
PWP -	Portable Work Platform
PWS -	Portable Workstation Stowage
RA&FP -	Resource Allocation & Functional Partitioning Panel
SSF -	Space Station Freedom
SSFP -	Space Station Freedom Program
STS -	Space Transportation System
SSRMS -	Space Station Remote Manipulator System
ULC -	Unpressurized Logistics Carrier
WETF -	Weightless Environment Training Facility
WP -	Work Packages

Abstract

The EVA overhead factor, as applied in this study, is the ratio of total man-hours in an EVA to the total man-hours of worksite tasks accomplished during that EVA. It is a dimensionless value that is used in the expression for predicting annual EVA crew time requirements for maintaining Space Station Freedom (SSF).

The value of the EVA overhead factor reflecting the current baseline SSF design may appear menacing; however, the EVA overhead factor is very sensitive to changes in design. By implementing the SSF EVA tools and equipment recommendations detailed in this report and emphasizing operational efficiency in the remaining phases of design, the EVA overhead factor can be reduced significantly.

This study focused on understanding the components that affect the EVA overhead factor, developing an EVA overhead factor as driven by the current baseline SSF design, and providing recommendations which will reduce the EVA overhead factor.

Introduction

The time available to perform external maintenance is a finite resource that is limited both by the number of EVAs that can be performed and by the 6-hour duration of all EVAs. Efficiency is critical for limited resources; therefore, all external tasks that require crew time must be carefully planned and managed. The SSF Program has divided these external tasks and their corresponding times into two categories: worksite tasks/times and EVA overhead tasks/times.

Worksite tasks are the goal of the EVA. They include the remove-and-replace, preventive maintenance (i.e., inspection, calibration, alignment, cleaning, etc.), and repair tasks that occur at the ORU's installed location. Worksite tasks assume that the crew, the necessary tools, and the equipment are at the worksite and configured to begin the task. The hardware provider is responsible for reporting the worksite task times to the SSF Program as the "mean-time-to-repair," or MTTR.

The EVA overhead tasks are setup and cleanup activities necessary to complete the worksite activities. This includes those tasks required for the astronaut to egress the airlock; acquire the necessary tools, equipment, and ORU; transport himself, the tools, and equipment to the worksite; restrain himself, the tools, and the equipment in the proper configuration to complete the worksite task; and the tasks necessary to perform the reverse of the aforementioned. The detailed tasks and the corresponding times required to perform the EVA overhead tasks are determined by the Mission Operations Directorate at the Johnson Space Center (JSC) in accordance with current Shuttle EVA capabilities and protocol.

Additional overhead tasks associated with the EVA are performed inside the SSF pressurized volume. These tasks, including prebreathe, Extravehicular Mobility Unit (EMU) donning, EMU checkout, EMU doffing, and EMU maintenance, and intravehicular monitoring of the EVA crew, require additional IVA crew time for each EVA. While the internal overhead task time impacts the total crew time required to support an EVA, it does not directly affect the EVA overhead task times and thus the external EVA requirements. Consequently, internal overhead tasks were not addressed in this study.

Purpose of the Study

The SSF Program's prediction of external maintenance requirements exceeds the current EVA capability. One way to reduce the magnitude of this discrepancy is to maximize the number of maintenance tasks that can be accomplished during each 6 hour EVA.

The number of maintenance tasks that can be accomplished is limited by the time required for the worksite tasks and the time required forEVA overhead tasks. While reducing individual worksite task times would decrease the net crew time requirements, the benefits would only be realized during EVAs where those worksite tasks occur. Reducing EVA overhead, though, affects every EVA–regardless of the worksite task to be performed.

The three major objectives in this study were to

1. Determine the components that affect the EVA overhead factor
2. Determine an EVA overhead factor based on performance of "generic maintenance tasks" with current SSF baseline designs
3. Identify ways to reduce that EVA overhead factor

Approach

The following approach was used to obtain the information necessary to achieve the objectives stated in the previous section:

1. Define the equation for the EVA overhead factor as it applies to SSF.
2. Evaluate applicability of any EVA overhead factors used previously in the SSF Program
3. Define the types of SSF Program EVA maintenance scenarios.
4. Establish ground rules and assumptions for each EVA maintenance scenario.
5. Develop detailed crew procedures for each "generic" EVA scenario based on the ground rules and assumptions.
6. Define components that affect EVA overhead task times.
7. Obtain validated primitive task times from past EVA data and neutral buoyancy testing, and apply those times to the detailed crew procedures.
8. Develop recommendations to reduce and control EVA overhead and, where possible, estimate the result of implementation.

EVA Overhead Factor Definition

As previously stated, the EVA overhead factor developed in this study is defined as the ratio of total man-hours spent outside the SSF pressurized volume to the total man-hours spent performing actual worksite tasks, based on a given set of assumptions and ground rules (see figure F-1). It is a direct multiplier in expressions for determining predictions of annual EVA crew time requirements.

$$\text{EVA Overhead Factor} = \frac{\textbf{Total length of an EVA in man-hours}}{\textbf{Total worksite time in man-hours}}$$

Assuming: A given design configuration and established operational constraints.

Figure F-1

The value of the EVA overhead factor is scenario-dependent. Any changes in the ground rules or assumptions used for developing the detailed crew procedures, whether design or operational, will modify the value of the EVA overhead factor. Note that use of a constant value for the EVA overhead factor is only valid for aggregate average values.

It is also important to understand that the relationship between the EVA overhead factor, the number of maintenance tasks that can be performed in an EVA, and the number of crew members performing the EVA is not necessarily linear. For example, adding a third crew member does not decrease the EVA overhead factor unless all the tools are provided to allow him or her to work independently.

Prior Estimate of the EVA Overhead Factor

In October 1989, the Level 2 Resource Allocation and Functional Partitioning Panel (RA&FP) issued a report stating that the external maintenance requirements for the SSF Program exceeded 1700 man-hours per year. Inherent in that number was an EVA overhead factor of 1.7.

This factor of 1.7 was expressed as a ratio of annual EVA man-hours per year to annual worksite man-hours per year. The 1.7 factor was used only as an aggregate average annual worksite overhead based on the following ground rules and assumptions:

1. The average worksite task = 1.5 hours, based solely on Work Package 2 data
2. Worksite overhead, which included only worksite setup, worksite teardown, and round trip translation, = 40 minutes
3. An uncertainty factor of 1.2 was included to account for granularity of estimates for such factors as tether management, status checks, etc.
4. SSF design had been optimized to minimize EVA overhead time

By definition, any changes to the ground rules or assumptions used in the EVA overhead factor development will change the value of the the EVA overhead factor. The October study did not include the time required to egress the airlock, acquire the tools and the Portable Work Platform (PWP), translate to the main CETA rail, acquire the replacement ORU from its stowage location, stow the failed ORU, translate back to the airlock, stow the tools and PWP, and ingress the airlock; therefore, an updated EVA overhead factor was required for this study.

Generic EVA Maintenance Timeline Types

When evaluating the types of external maintenance tasks that will occur on the SSF, they separate naturally into two categories according to their location:

1. Integrated Truss Assembly (ITA) Maintenance Tasks–those occurring on ORUs located on the truss elements, the pallets, and any other area accessible from the CETA cart.
2. Module pattern Maintenance Tasks–those occurring on ORUs located on the exterior surfaces of Nodes, the Habitation and Laboratory Modules, and the International Modules.

The actual performance of the EVA overhead tasks differs slightly for these two locations, requiring the development of two generic timelines: the Baseline ITA Maintenance EVA and the Baseline Module Pattern Maintenance EVA.

Ground Rules for EVA Maintenance Timeline Development

Deriving an aggregate EVA overhead factor value requires the development of detailed EVA maintenance timelines depicting "generic" maintenance tasks. These timelines provide all of the information necessary to compute the EVA overhead factor. The ground rules used to develop the timelines were as follows:

1. **A nominal time of 6 hours of useful EVA time is available, beginning with the time the crew turns on their EMU batteries and ending when the airlock hatch is closed. A pad of 15 minutes is available at the end of the EVA for overruns.**

   BASIS–nominal period of EVA time available to a customer as an optional service is 6 hours; however, the EMU is designed for 7 hours, which includes 1/2 hour of reserve, 15 minutes for egress, and 15 minutes for ingress;

2. **There will always be two crew members outside the SSF pressurized volume during an EVA; however, they can work independently on different parts of the SSF.**

   BASIS–current EVA flight rules incorporate a buddy system requiring two crew members to be EVA simultaneously. Crew rescue and emergency return to the airlock studies have indicated that it is safe for EVA crew members to work independently on different sections of the SSF;

3. **Timelines will be developed to maximize efficiency with EV1 and EV2 working in parallel wherever possible.**

   BASIS–provides a basis for an efficient but safe EVA timeline, allowing completion of the maximum number of worksite tasks with the lowest EVA overhead factor given a specific design and configuration.

4. **A nominal worksite task time of 1 hour will be used.**

   BASIS–the worksite task times for all reported ORUs range from .02 hours for WP2's waste gas dump assembly to 12 hours for WP4's PV cable set, with an average time of 1.1 hours. As of the date of the database query used to obtain this information, 74% of the 4642 worksite tasks are equal or less than the calculated average;

5. **Worksite tasks can be accomplished by one crew member.**

   BASIS–data provided by the hardware developers indicate that 75% of the worksite tasks are designed and optimized for completion by one EVA crew member; and

6. **The timelines will be populated with the maximum number of 1 hour worksite tasks that can be accomplished during the 6-hour EVA.**

   BASIS–provides a basis for an optimum EVA overhead factor given a specific scenario.

The assumptions used for each crew procedure are unique to that timeline and are discussed in the "RESULTS" section of this report.

Crew Procedure Development

The timelines include all EVA overhead tasks chronologically encountered during an EVA. This includes airlock egress, tool acquisition, PWP acquisition, translation to main CETA rail and the logistics carrier, ORU acquisition, translation to the worksite, worksite setup, worksite tear down, translation to the logistics carrier, ORU stowage, translation to the airlock, PWP stowage, tool stowage, and airlock ingress.

The EVA overhead tasks are further broken down into sub-tasks, or "primitives." The primitives provide the detailed steps of the EVA overhead tasks, describing equipment operations as defined by the equipment designer. Where sufficient design detail was not available, assumptions were made and are noted in the "Assumptions" column of the timeline.

The timelines are then assessed for instances where the two crew members are working in parallel. An indication is provided in the "Assumptions" portion of the timeline, and no time is added to the timeline. The format for the primitive task times is HH:MM:SS. When tasks are performed in parallel with the other crew member, the task time is indicated as 0:00:00 centered in the task time column. When a primitive time is included in the primitive task time immediately preceding it, the time is shown as 0:00:00, and is right justified in the task time column. Primitive tasks that can only be partially completed before the other crew member completes his tasks are indicated as "partially parallel," and the residual time is added to the task time.

EVA Overhead Time Drivers

The time required for EVA task primitives is driven by three areas: equipment design and configurations, individual task performance, and astronaut-unique characteristics. Each of these contributors must be considered when developing primitive task times and making recommendations for deducing EVA overhead. All of these areas can cause a large variation in individual task times.

The operational requirements of every piece of equipment with which the astronaut must interface during the performance of EVA overhead tasks will influence EVA overhead task times. A large number of the EVA overhead primitive tasks, such as tethering to an object, are repeated throughout the EVA. A design change in a single piece of equipment resulting in a small individual time savings can have a large impact on the total EVA overhead time. Figure F-2 shows examples of design-related criteria that will affect EVA overhead task times.

Design-Related Factors Affecting EVA Overhead

ORU
Size (weight, volume)
Tether points (#, location)
Handrails (#, location)
Bolts/fasteners (#, type, location)
Soft dock capability
Connectors (#, location)
Temporary stowage capabilities (CETA cart, at worksite)
Installation methods (logistics carrier, worksite)
Accessibility at worksite

Logistics Carrier
Quantity
Location
Accessibility from CETA cart
Access to ORU
ORU attachment method
connectors to ORUs

Crew Restraints
Installed foot restraints (#, placement)
Portable foot restraints (#, stowage location)
Foot restraint ingress aids (#, placement)

Transport Mechanism
Crew required
ORUs/equipment transferred simultaneously
Control capabilities
Weight capacity
Size capacity

Translation Aids
Handrails (#, placement)
CETA cart (#)

Figure F-2

Performing EVA is a skill that requires a tremendous amount of practice due to the unique environment of space. The EVA crew members are constrained by various performance factors because of the limitations imposed by the EMU, strict tether protocol requirements, and absence of gravity. Figure F-3 describes some of the performance factors that can affect EVA overhead task times.

Task Performance Factors

Tethers (#, placement)
Tether snags
Reach envelope (EMU constraint)
Sight constraints (EMU limitation)
Lighting
EMU operation
Restraint aids
Handrail placement

Figure F-3

There are also astronaut-unique features that can affect EVA overhead task times. Figure F-4 lists some of these factors. Although astronaut-unique factors are not specifically accounted for in this study, it must be understood that these factors can cause a wide variation in EVA task times.

Astronaut-Unique Factors

Size (i.e., height, arm length)	Training (type, duration, frequency)
Strength (hand, upper body)	Attitude
Stamina	EMU fit
Health	Fatigue
Coordination	

Figure F-4

EVA Task Primitive Times

At the beginning of this study, engineering estimates were used to develop the task time estimates. These estimates were validated and updated using data from two sources: previous flight EVAs and Weightless Environment Training Facility (WETF) testing at the Johnson Space Center.

While actual flight experience is the best source of valid timeline data, WETF testing can also provide valuable data points. This type of neutral buoyancy testing has proved to be an effective tool in simulating the space environment. Although there is not always a one-to-one correspondence between the entire WETF test time and an actual EVA time because of test-specific activities, there are direct correlations between WETF and EVA task primitives.

Three series of WETF tests were conducted specifically for this study. They had two objectives:

1. To supplement flight video data for tasks where no analogous flight data were available and to provide additional data points for determining average primitive task times
2. To provide a preliminary crew assessment of the "generic ORU box design" discussed in Appendix G of this report

Six astronauts participated in the test. Test subjects were chosen who were experienced in EMU operations and who had either actual Shuttle EVA experience or who had received a significant amount of training in the WETF. This was done to minimize the effects of a lack of training on a specific task.

Three test runs were conducted during each WETF test. The first was a familiarization run used to obtain photographs and developmental comments on the ORU. The second and third runs were used to obtain timeline information from each crew member. A complete copy of the test plan and the test report are included in Attachment 1.

Audio and video footage of all WETF tests was recorded with a Greenwich Mean Time code window provided by the Photography and Television Technology Division at JSC.

A team of JSC Mission Operations Directorate EVA Crew Systems personnel was established consisting of people with no prior involvement in this study. This team was given the following objectives:

1. Obtain video media containing the time code window from the following sources: STS-6, 41-B, 41-C, 41-G, 51-A, 51-I, 51-D, and 61-B, Skylab, and the WETF tests performed for this study
2. Review the tapes for tasks analogous to SSF EVA overhead tasks shown in the generic procedure, and extract the timeline information. The time should begin upon completion of the previous task and end when the next task is started
3. Enter the timeline information into a database for traceability and further analysis by the External Maintenance Task Team

A condensed copy of their report is shown in Attachment 2.

Data from flight videos was obtained for tasks equivalent to the Space Station EVA overhead tasks or when analogies to Space Station overhead tasks were apparent. Data obtained from the WETF video gave preference to the crew members who had the least difficulty performing the task.

After the database was complete, all "like" primitive tasks were grouped together with their corresponding times, and an average was calculated for each primitive task. Preference was given to flight data when WETF tests did not use flight-like hardware or the task times for WETF data were significantly greater than the flight times. A complete listing of the source data and the primitive task time averages is shown in Attachment 3.

These primitive task averages and their sources were then entered into the appropriate place on the EVA maintenance timelines. Engineering estimates were applied to the primitive tasks where sufficient design detail was not available or analogous task times could not be obtained.

Recommendation Methodology

Recommendations were formed based on an analysis of the the timelines. Preliminary timelines and recommendations were developed February, 1990. During the External Maintenance Task Team midterm meeting held at JSC in April 1990, a splinter group was formed to evaluate those timelines.

First, the ITA and Module Pattern Timelines were reviewed in the splinter group for areas where operational efficiency could be improved. Secondly, a four-page list of candidate recommendations was assembled. These recommendations were presented to all attendees during the summary presentations.

After the midterm meeting, the candidate list of recommendations was reviewed, updated, and rationale for each recommendation was added by Mission Operations Directorate personnel at JSC. The final list of recommendations appears in section 6.0 of this appendix.

Results and Discussion

This study resulted in the development of three timelines. The Baseline ITA Maintenance Timeline, and the Baseline Module Pattern Timeline were developed to indicate use of equipment currently baselined in the SSF Program. The third timeline was developed to show the EVA scenario that results when all equipment is designed and optimized for efficiency and for use by a single EVA astronaut.

Baseline Timeline Assumptions

As stated in the definition, an EVA overhead factor is developed using a given set of assumptions, and any deviation from these assumptions will change its value. The following list defines the assumptions and their basis as used in development the Baseline ITA Maintenance Timeline :

1. **Two crew members are EVA at the same time**

   Basis–current Shuttle Program protocol;

2. **Space Station configuration is as currently baselined, and equipment operations are as described by the developer**

   Basis –assumption used to determine baseline EVA overhead factor;

3. **Portable foot restraints are permanently installed on the PWP stowage container and on the tool box**

   Basis–preliminary design review information provided by the developing contractor;

4. **EV1 and EV2 egress together, work either together or independently as required to accomplish the overhead tasks and worksite tasks, then ingress together**

   Basis–Current EVA protocol for Airlock Egress/Ingress, and optimization of crew time with hardware provided;

5. **There is one CETA cart capable of transporting both crew members, a Portable Work Platform, and one ORU**

   Basis–preliminary design information provided by the developer; however, specific procedures for attaching equipment to the CETA cart have not been defined as of this report date;

6. **The Mini-Work Stations, clothesline device, and tools are stowed in the External Support Equipment and Tool stowage container (ESE&T), or toolbox, located on the airlock**

   Basis–PDR data provided by the developer; also, the toolbox is similar in design to the Hubble Space Telescope toolbox;

7. **The ORUs are bolted down with 4 bolts in the ULC and at the worksite and only blind mate connectors exist**

   Basis–an assumption, specific design details of the logistics carriers were not available as of this report date;

8. **The EMU lights constitute the only lighting that is required at the worksite**

   Basis–an assumption that saves setup of portable lighting in the timelines;

9. **The ORUs can survive without thermal conditioning from the time they are removed from the ULC until they are installed at the worksite**

   Basis–an assumption that saves any manipulation of thermal blankets or some similar protective covering;

10. **The clothesline device is capable of transferring equipment to and from the worksite and has the following characteristics**

    a. **Ability to carry one item at a time**

    b. **A hook to which the items to be transferred may be attached**

    c. **The ability to handle large ORUs (up to 36x42x84)**

    d. **The ability to be adjusted to the proper length at worksites of various distances**

    Basis–information provided at the preliminary design reviews by the developer;

11. **All necessary handholds and translation aids exist and are in the ideal locations**

    Basis–an assumption that omits the need to obtain and install translation aids (i.e., handrails);

12. **Translation across truss struts is permissible and will not damage any protective coatings**

    Basis–an assumption that minimizes constraints on the astronauts as they translate to and from the worksite;

13. **An unpressurized logistics carrier contains all of the ORUs necessary to complete the EVA**

    Basis–an assumption that eliminates logistics constraints;

14. **Short tasks such as EMU checks can be performed during the allotted worksite task time and are not necessary during performance of EVA overhead tasks**

    Basis–an assumption that short tasks can be done in parallel while the other crew member is working, thus not affecting the task times;

15. **The PWP is stored in three separate pieces in a protective container located on the airlock, only two of which are necessary for these timelines**

    Basis–based on information provided by the developer at PDR; only the PWP PFR and small stanchion will be used, because it was assumed that additional lighting was not necessary;

16. **The astronauts must set up the PWP at each worksite**

    Basis–baseline operations as described by the developer;

17. **The astronauts must remove the PWP from each worksite once finished**

    Basis–baseline operations as described by the developer at PDR;

18. **Truss struts and other equipment need not be removed in order to transfer objects from the CETA cart to the worksite**

    Basis–an assumption that these type of requirements for accessing a worksite are not "normal operations"; and

19. **There are two tasks to be performed, one on the port side and one on the starboard side, both inside the Alpha joint**

    Basis–an assumption providing maximum distance apart without inducing the timeline uncertainties associated with crossing the alpha joint;

Assumptions 1 through 13 are the same for the Baseline Module Pattern Maintenance EVA; however, the following additional assumptions are applicable:

1. **Handrails exist in places that allow translation to each worksite**

   Basis–an assumption that is applicable following the first visit to each worksite based on preliminary information provided by the developer;

2. **A slide wire exists next to each set of handrails**

   Basis–as assumption based on information provided by the developer;

3. **The ORU is accessible from the slidewire while in the foot restraints at the worksite**

   Basis–an assumption that eliminates the need for one of the stanchion's functions;

4. **Sufficient foot restraint ingress aids exist at the worksite so that the PWP stanchion is not required**

   Basis–an assumption, which, coupled with #3 above, eliminates the need for a stanchion; and

5. **The micro-meteoroid debris shield cannot be damaged from the EVA crew member translating across the module or from the ORU impacting it**

   Basis–an assumption which reduces constraints on the crew members while translating to the worksite.

Baseline Timeline Scenarios

The following is a description of the Baseline ITA Maintenance Timeline scenario shown in Attachment 4. Photographs taken during the WETF tests and preliminary design review drawings are included where applicable.

The baseline timeline begins with the EV crew members in the Space Station airlock, preparing to egress. Figures F- 5, 6, and 7 depict some of the primitive tasks required to egress the airlock. Figure F-8 is a drawing of the current concept for external airlock outfitting. It shows the location of the hatch in relation to the External Support Equipment & Tool (ESE&T) stowage containers (toolboxes), the Portable Work Platform stowage containers, and the CETA rail airlock spur.

Figure F-5. EV1 tethers to EV2's right waist tether, then EV2 secures left waist tether to airlock

Figure F-6. After hatch opened, EV1 exits airlock and secures left waist tether to CETA safety tether D-ring #1, and EV2's right waist tether to D-ring #2

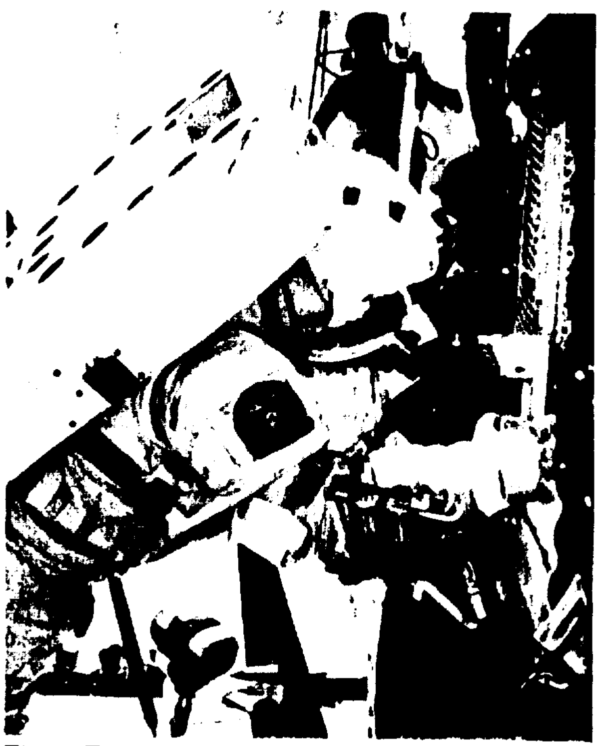

Figure F-7. After both crew members egress the airlock, they remove the safety tethers from their pouches and unlock them

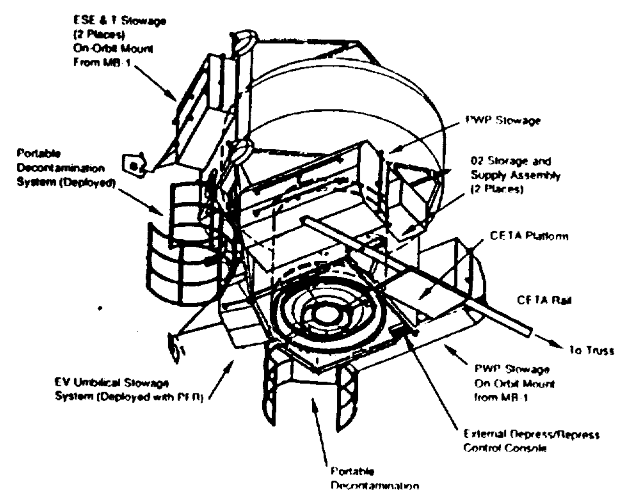

Figure F- 8. PDR drawing depicting Space Station Freedom airlock external outfitting

After egressing the airlock, each crew member translates to one of the External Support Equipment and Tool (ESE&T) stowage containers, shown in Figure F-9. Here, the astronaut ingresses the foot restraints, opens the ESE&T doors, and gets the mini-workstation and the necessary tools. The photographs in Figures F-10, 11, and 12 depict a crew member tethering to the mini-workstation, attaching it to the EMU, then tethering the tool to the mini-workstation.

After all of the necessary tools have been obtained, the crew members close the ESE&T stowage container, egress the foot restraints, and translate to the Portable Work Platform (PWP) stowage container. A drawing of the PWP stowage container is shown in Figure F-13, and a drawing of the PWP in Figure F-14. One crew member ingresses the foot restraints, opens the doors, tethers to the PWP foot restraint, releases it from the stowage container, and passes it to the other crew member, who attaches it to the CETA cart. Meanwhile, the first crew member obtains the PWP stanchion, closes the doors, egresses the foot restraints, translates to the CETA, and attaches the stanchion to the CETA. Figure F-15 shows PDR drawings of the CETA cart; however, the concept for attaching the PWP and stanchion to it has not been determined.

The next EVA overhead task category involves translating on the CETA cart across the airlock spur mechanism, shown in Figure F-16. Both crew members ingress the CETA PFRs, as shown in Figure F-17, translate across the rail spur mechanism to the main CETA rail, and translate to the logistics carrier as shown in Figure F-18.

Specific operations information for the logistics carriers was not available because of the early stage of the design. The timeline assumes that EV1 must take the clothesline and a CETA PFR, install them on the logistics carrier, open the logistics carrier doors, remove the ORU's launch restraints, remove the ORU from the carrier, attach it to the clothesline, and transfer it to the CETA cart. Then EV2 would release the ORU from the clothesline and attach it to the CETA cart. Meanwhile, EV1 closes the logistics carrier doors, removes the PFR and the clothesline from the logistics carrier, translates back, installs them on the CETA cart, and both crew members ingress the CETA PFRs to translate along the CETA rail to the worksite.

After parking the CETA cart at a point adjacent to the worksite, the crew members egress the foot restraints, and EV1 tethers to the clothesline end as shown in Figure F-19. Figures F-20, 21 and 22 show EV1 tethering to the PFR, releasing it from the CETA cart, and attaching it to the Hubble Space Telescope's semirigid tether. The crew member then translates along the truss struts to the pallet leg, passes through the pallet leg to the front of the pallet, attaches the clothesline to the pallet, and adjusts the clothesline length, as shown in Figures F- 23, 24, 25, and 26, respectively. This is the procedure depicted in the baseline timeline. During the WETF tests, some test subjects preferred to transfer to the worksite carrying only the clothesline, then transfer the PWP PFR to the worksite on the clothesline. This procedure is shown in Figures F-27-30. Once the PFR is at the worksite, EV1 installs the PFR in the PFR socket on the pallet as shown in Figure F-31, ensuring proper PFR orientation.

While EV1 installs the PWP PFR, EV2 releases the stanchion from the CETA cart, attaches it to the clothesline, and transfers it to the worksite, as shown in Figure F-32. Figure F-33 shows EV1 preparing to install the stanchion after releasing it from the clothesline.

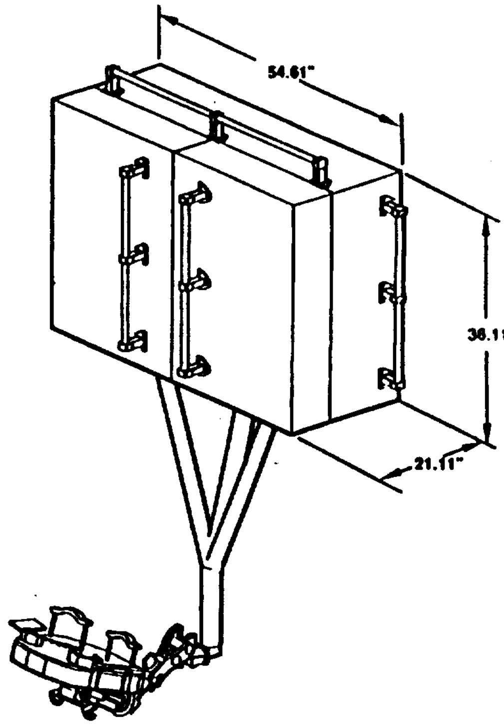

Figure F-9. PDR drawing of external support equipment and tools stowage container

Figure F-10. EVA crew member tethers to the mini-workstation and simulates removal from ESE&T stowage container

Figure F-11. EVA crew member attaches the mini-workstation to the EMU

Figure F-12. EVA crew member tethers to a tool and simulates removal from ESE&T stowage container

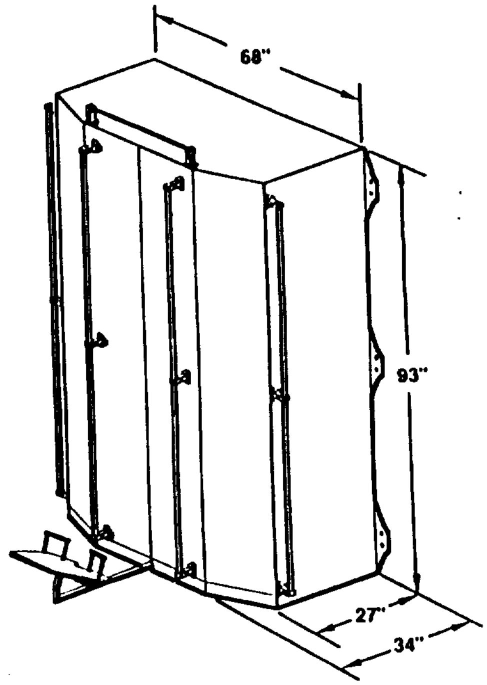

Figure F-13. PDR drawing of the Portable Workstation stowage container

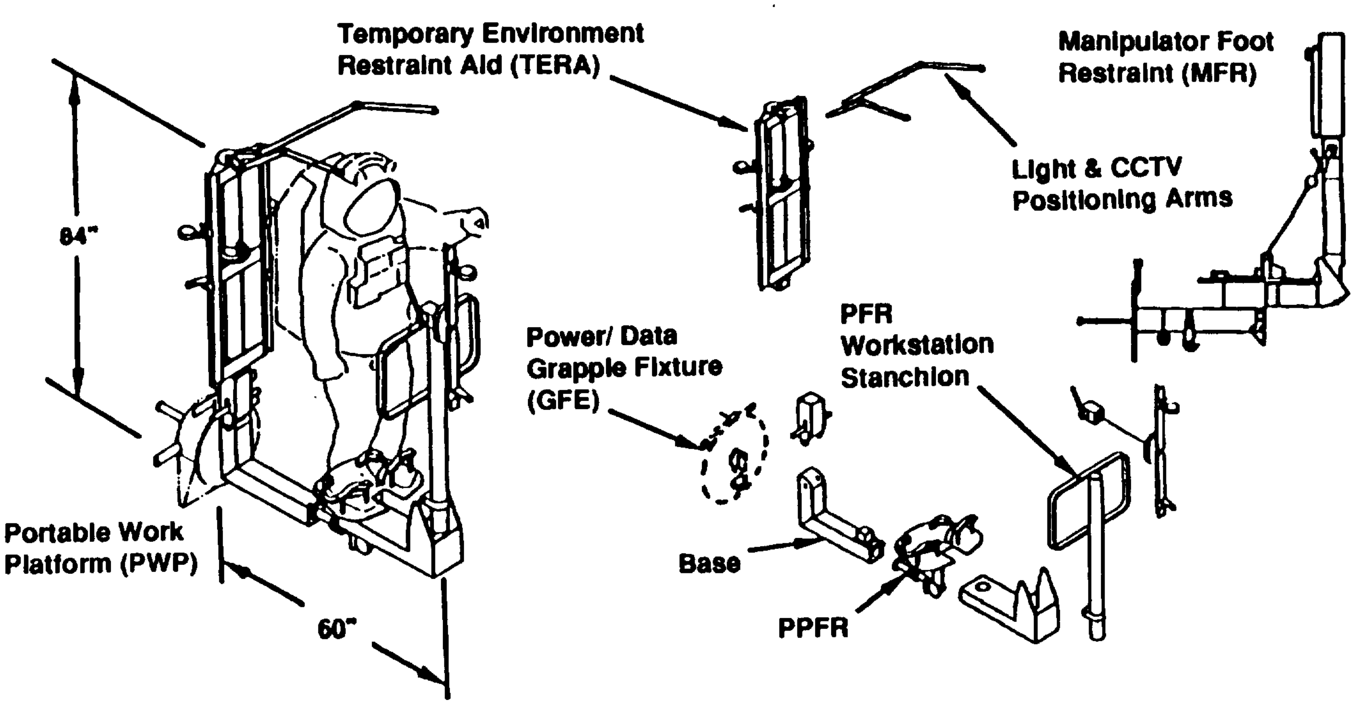

Figure F-14. PDR drawings of the PWP foot restraint and stanchion

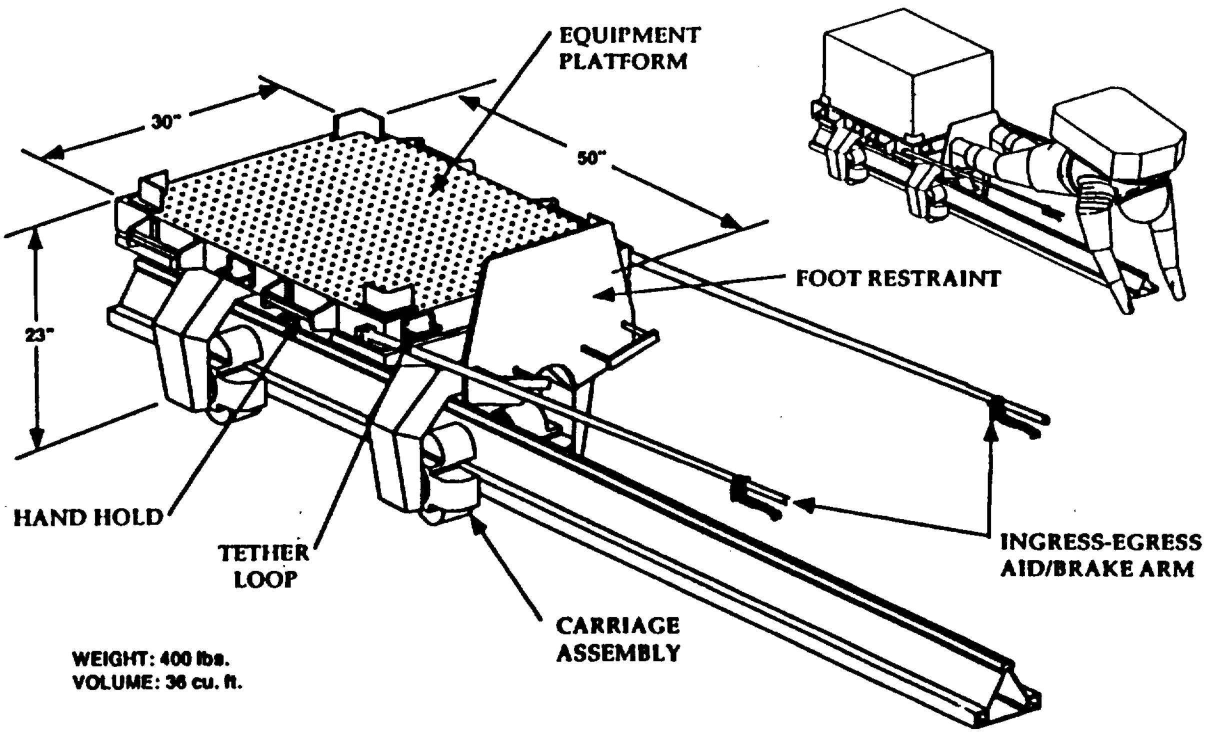

Figure F-15. PDR drawing of the CETA cart

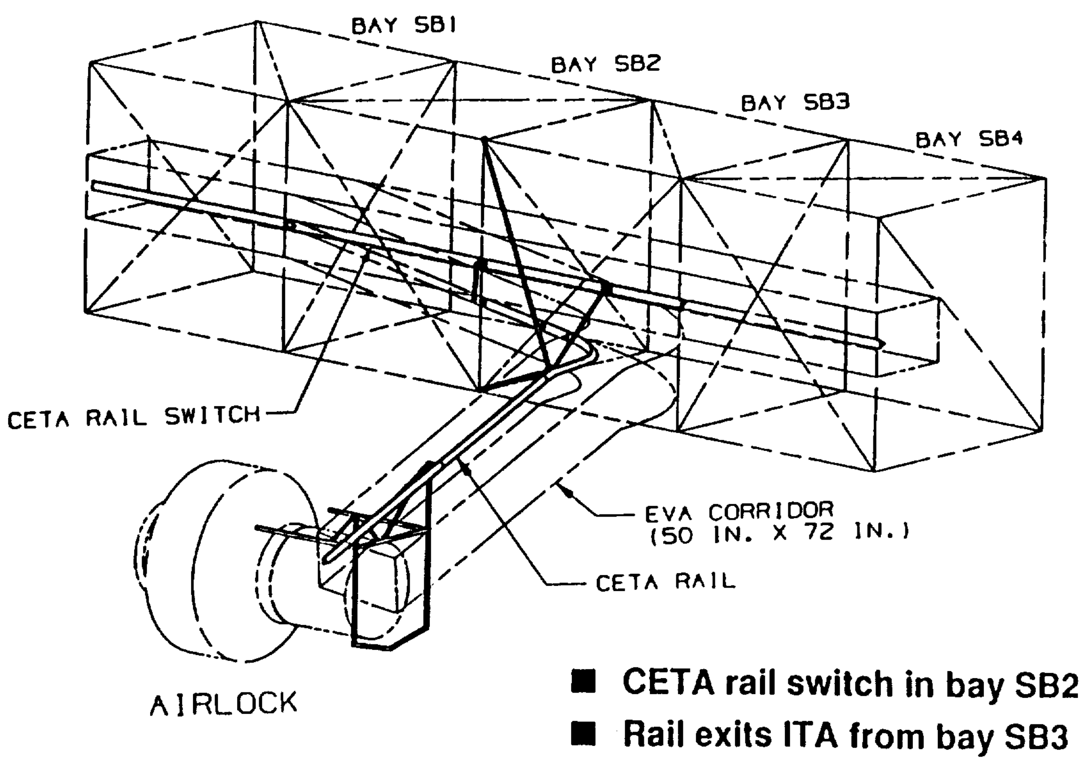

Figure F-16. PDR drawing of CETA rail routing from the airlock

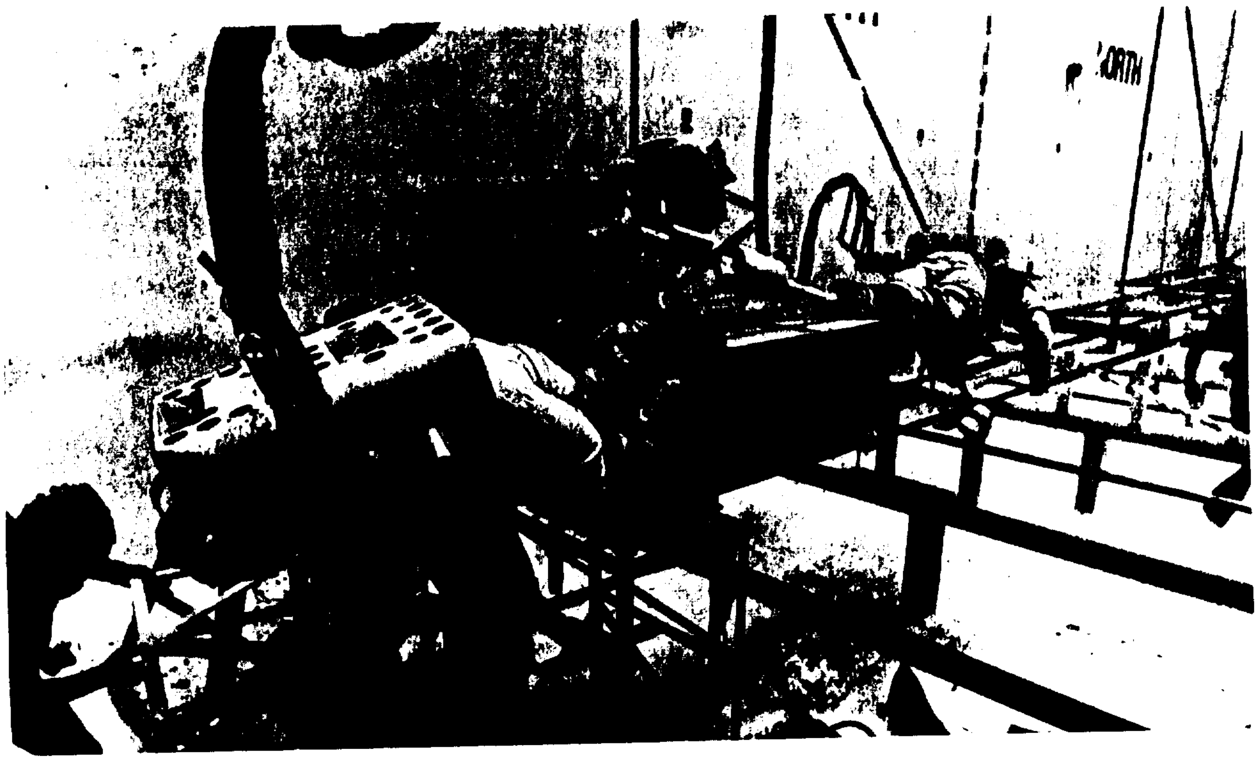

Figure F-17. Crew members ingress the CETA foot restraints

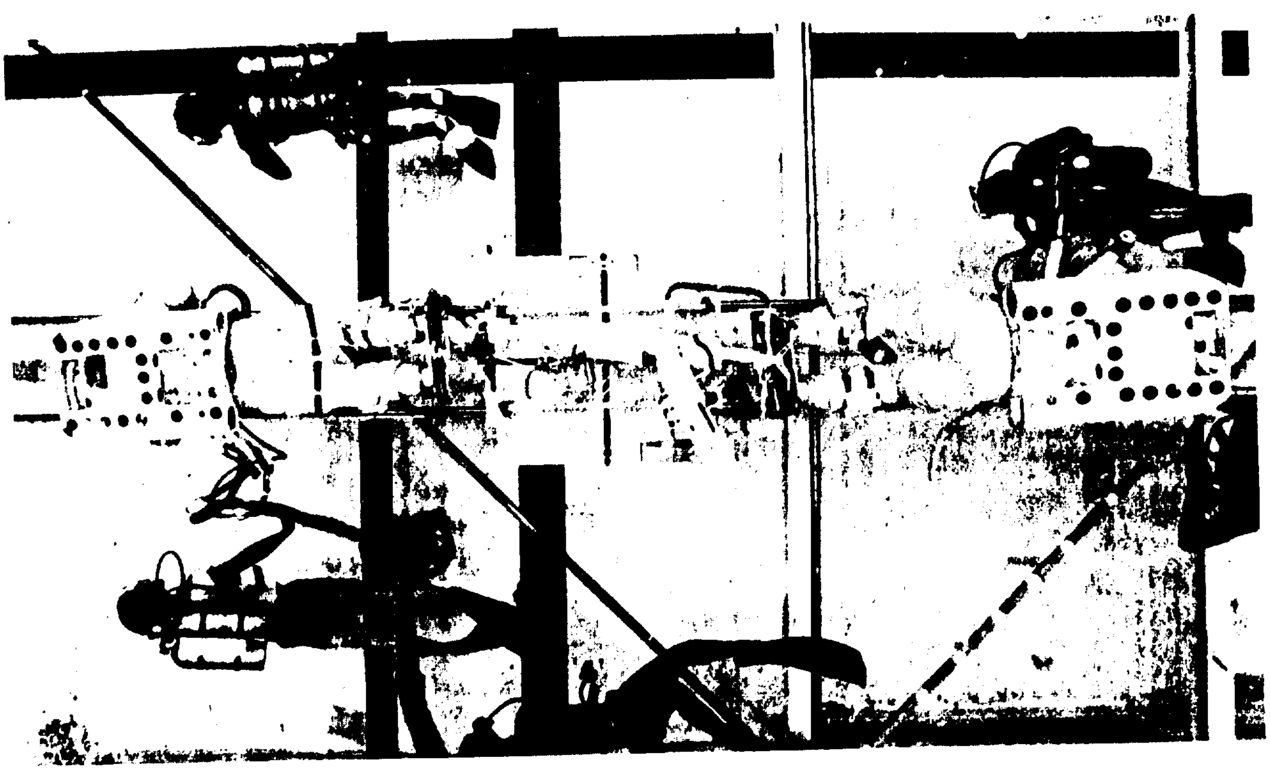

Figure F-18. Crew translating along the truss to the worksite

Figure F-19. Crew tethers to the clothesline end

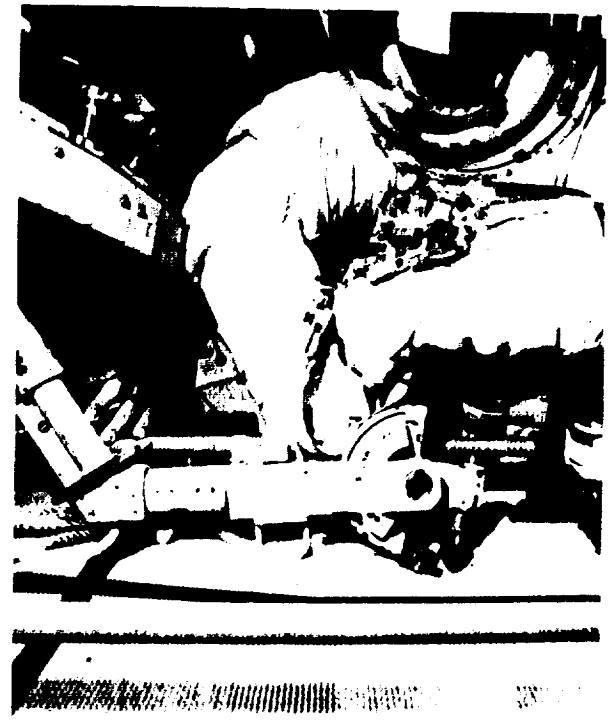

Figure F-20. Crew releases the wrist tether and attaches it to the foot restraint

Figure F-21. After tethering to the foot restraint, it is released from the CETA

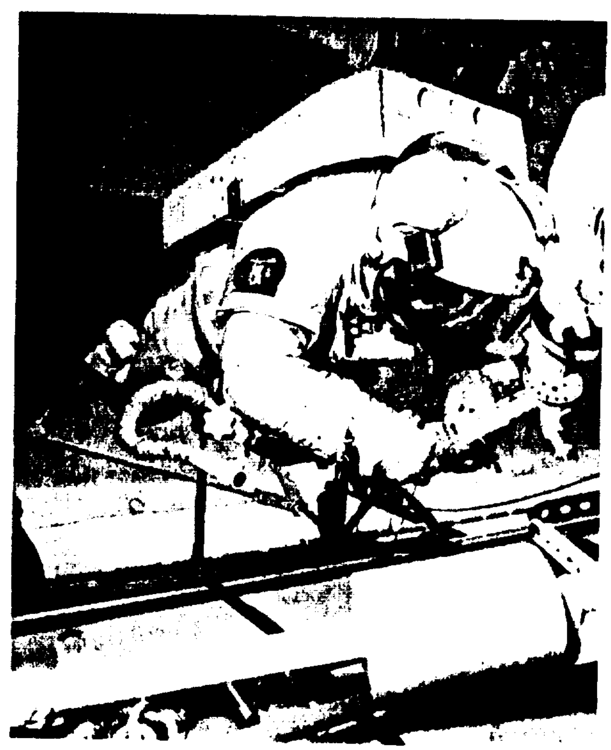

Figure F-22. Crew member attaches the foot restraint to the Hubble Space Telescope semi-rigid tether

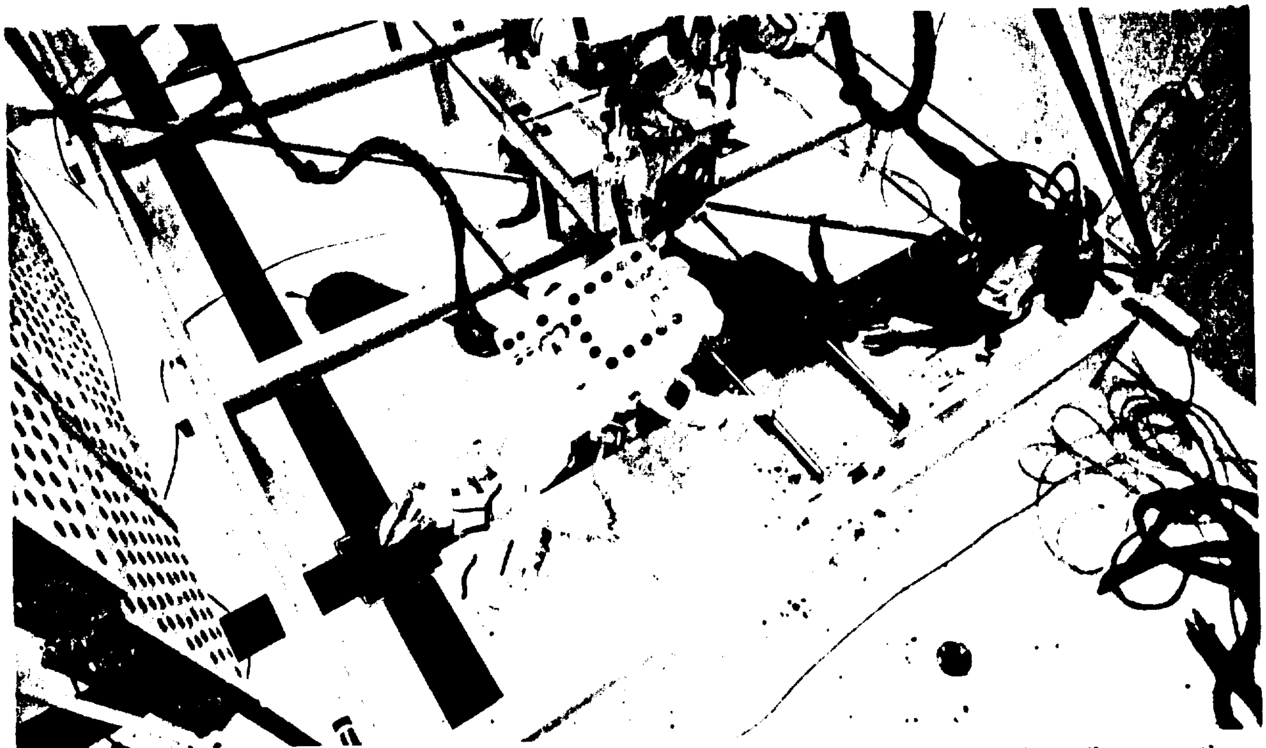

Figure F-23. Crew member translates with the clothesline and foot restraint along the CETA rail truss to the pallet leg

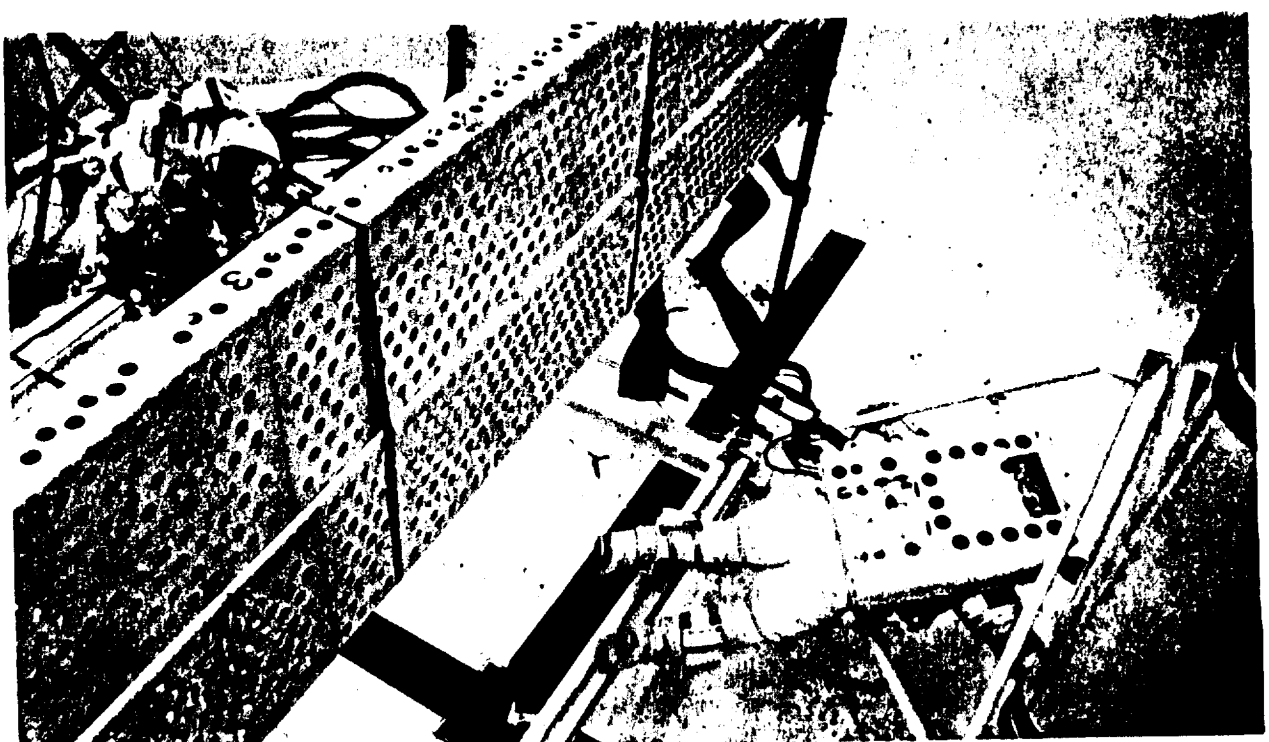

Figure F-24. Crew translates along the pallet leg to the outside of the pallet

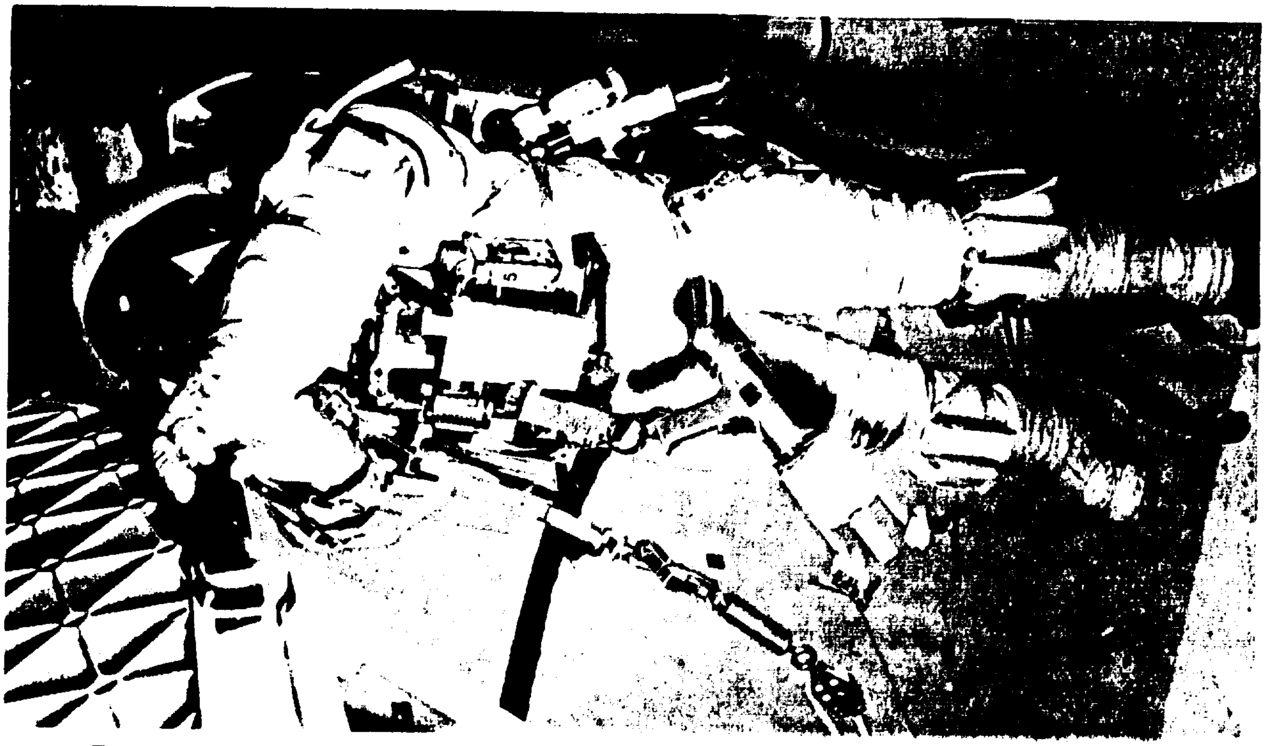

Figure F-25. The clothesline end is released from the wrist tether, then attached to the pallet leg

Figure F-26. The clothesline is adjusted to the proper length

Figure F-27. The PFR is attached to the clothesline

Figure F-28. Wrist tether is released from the PFR

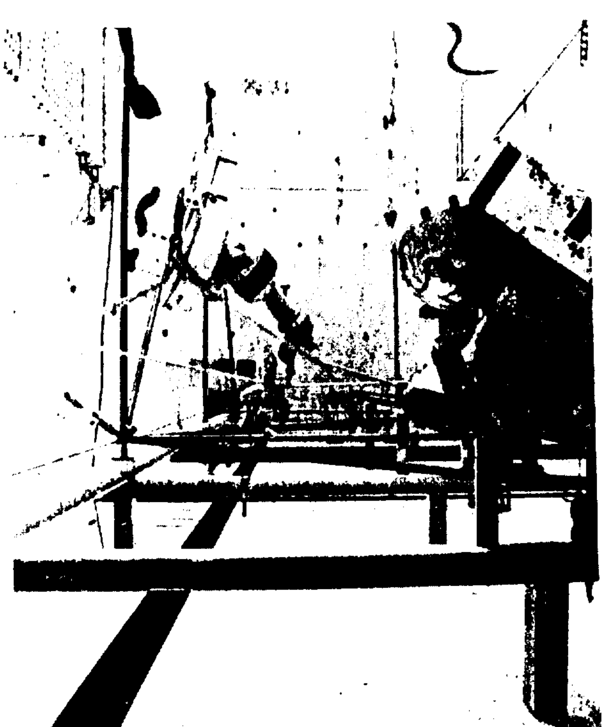

Figure F-29. The PFR is transferred to the worksite on the clothesline

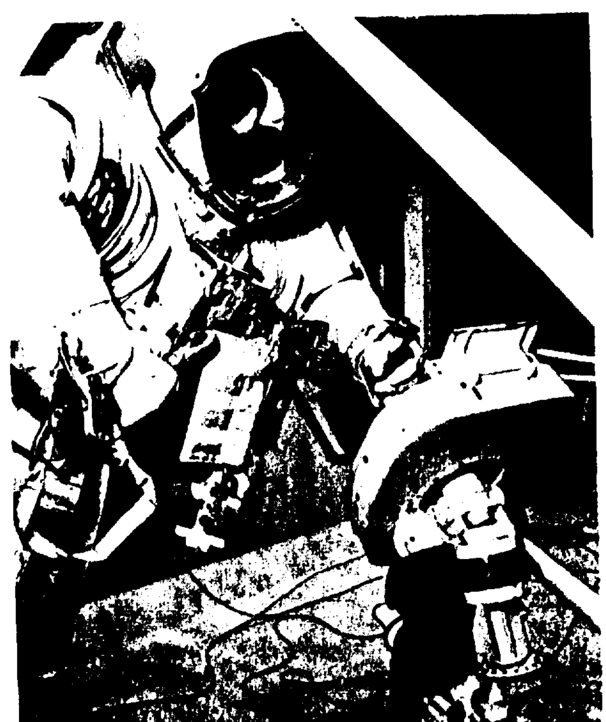

Figure F-30. At the worksite, EV1 tethers to the portable foot restraint and releases it from the clothesline

Figure F-31. EV1 installs the foot restraint in the PFR socket, then inserts the pin, and releases the tether

Figure F- 33. EV1 releases the stanchion from the clothesline and installs it at the worksite

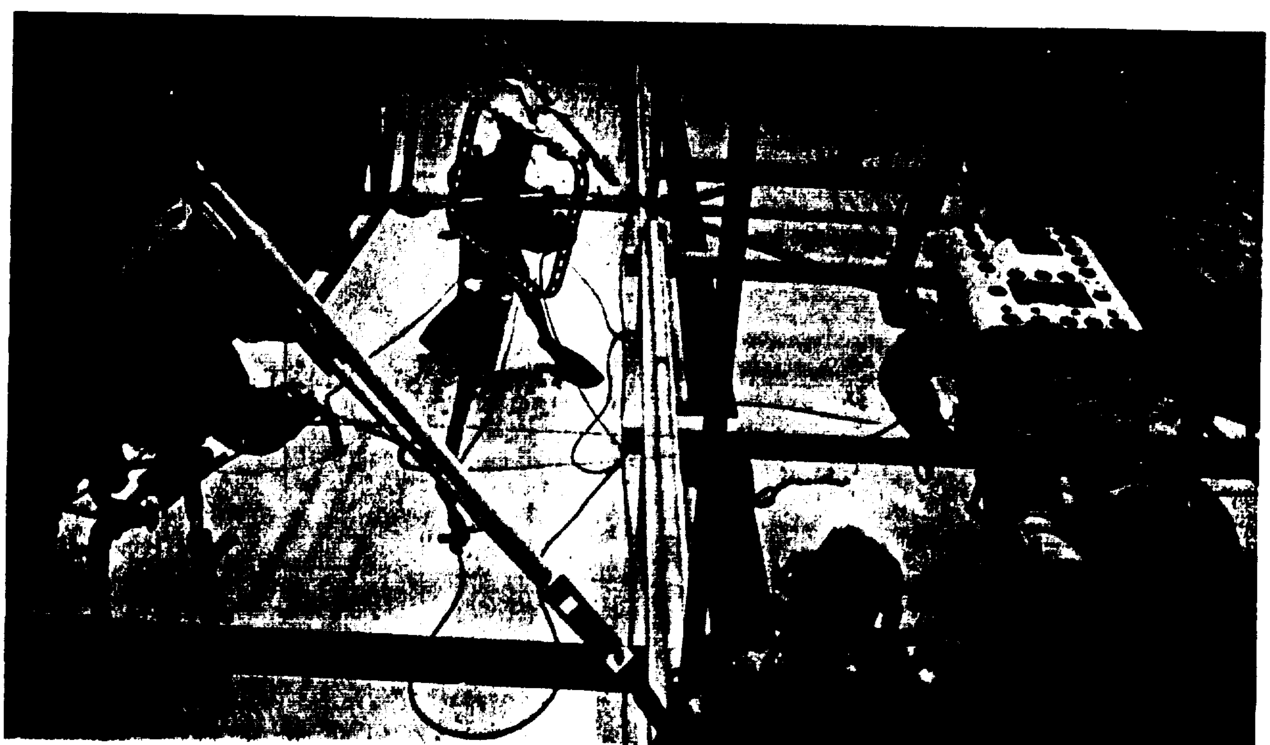

Figure F-32. EV2 transfers the stanchion to the worksite on the clothesline

Working in parallel with EV1, EV2 attaches the ORU to the clothesline, releases the ORU from the CETA, and transfers the ORU to the worksite, as can be seen in Figures F-34-36. Figures F-37-41 begin when the ORU reaches the pallet. The EV1 guides the ORU through the pallet leg, releases it from the clothesline, and translates to the PWP PFR, ingresses the PFR, and manipulates the spare ORU around the worksite to temporarily stow it on the PFR stanchion.

At this point the worksite tasks can begin. While EV1 performs the worksite task, EV2 translates to the logistics carrier, gets the 2nd ORU, takes it to the second worksite, and tethers it near the second worksite. Then EV2 returns to the first worksite to help EV1 tear down the worksite, stow the failed ORU, and set up the second worksite. After the second worksite task is complete, the worksite is torn down, the ORU stowed in the logistics carrier, and the crew members perform all of the tasks necessary to get back to the airlock, stow their tools and support equipment, then ingress the airlock.

The Baseline Module Pattern Timeline, shown in Attachment 4, follows the same general procedure; however, the portable work platform is not used, and translation to the worksite is very different. After obtaining the tools, the portable foot restraint, and the ORU, crew members must translate hand-over-hand along the handrails, pushing the ORU along the slide wire in front of them.

The Baseline Module Pattern Timeline scenario shows that two worksite tasks can be completed in less time than two ITA tasks can be completed. This difference may be aggravated by the fact that the Baseline Module Pattern Timeline contained more design-related assumptions than in the Baseline ITA Timeline. When assumptions were made in this study, they were chosen so the overhead times required were minimized.

Baseline EVA Overhead Factor

The EVA overhead factor uses the information provided from the two timelines to determine the EVA overhead factor.

The EVA overhead factor for the Generic ITA Maintenance EVA is as follows:

$$\text{Baseline ITA EVA Overhead Factor} = \frac{(5.9\ \text{hours})(2\ \text{crew})}{(2\ \text{hours of tasks})(1\ \text{crew})} = 5.9 \approx 6$$

Given: Ground rules and assumptions stated in this study

The EVA overhead factor for the Module Pattern Maintenance EVA is as follows:

$$\text{Module Pattern EVA Overhead Factor} = \frac{(4.8\ \text{hours})(2\ \text{crew})}{(2\ \text{hours of tasks})(1\ \text{crew})} = 4.8 \approx 5$$

Given: Ground rules and assumptions stated in this study

The number of ORUs located on the module pattern was not available at the time of this report; therefore, it was not possible to determine the impact on the EVA overhead factor. For this study, it was assumed that the majority of the ORUs are located on the truss assembly; therefore, EVA overhead factor of 6 was used.

Figure F-34. EV2 tethers to the ORU

Figure F-35. The ORU is released from the CETA

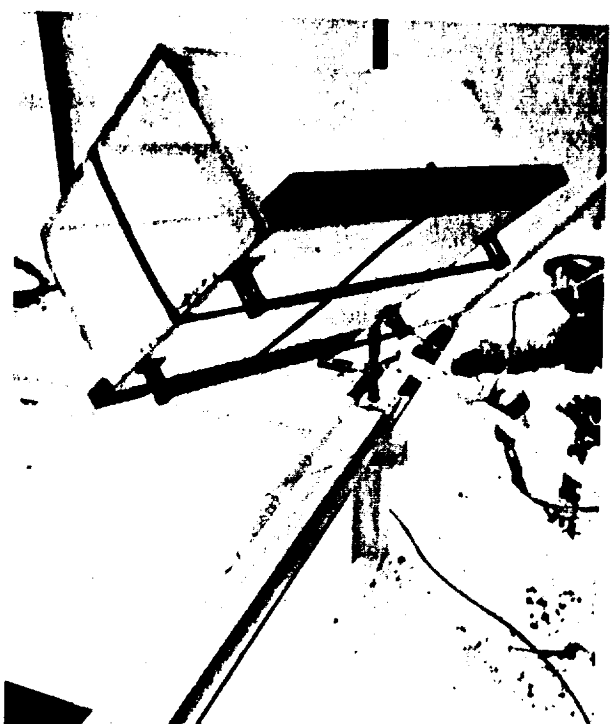

Figure F-36. The ORU is attached to the clothesline and transferred to the worksite

Figure F-37. EV1 tethers to the ORU and releases it from the clothesline

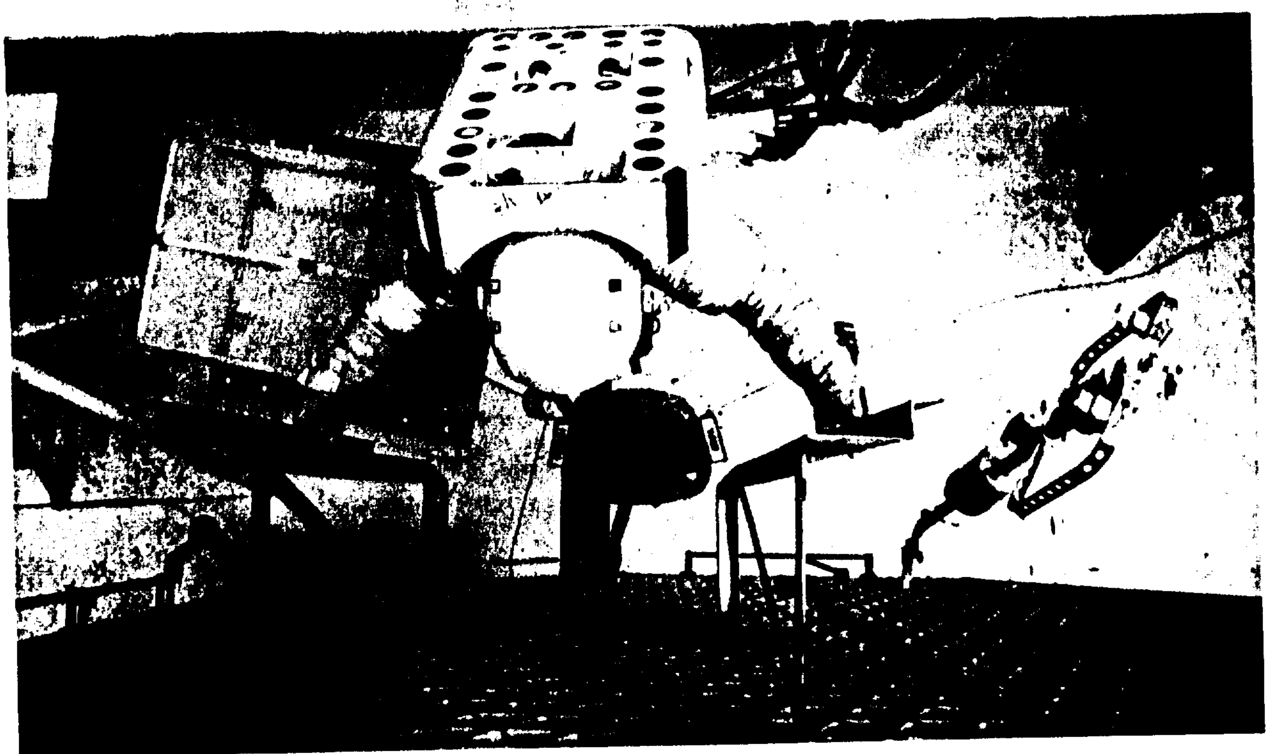

Figure F-38. EV1 takes the ORU to the worksite and ingresses the foot restraint

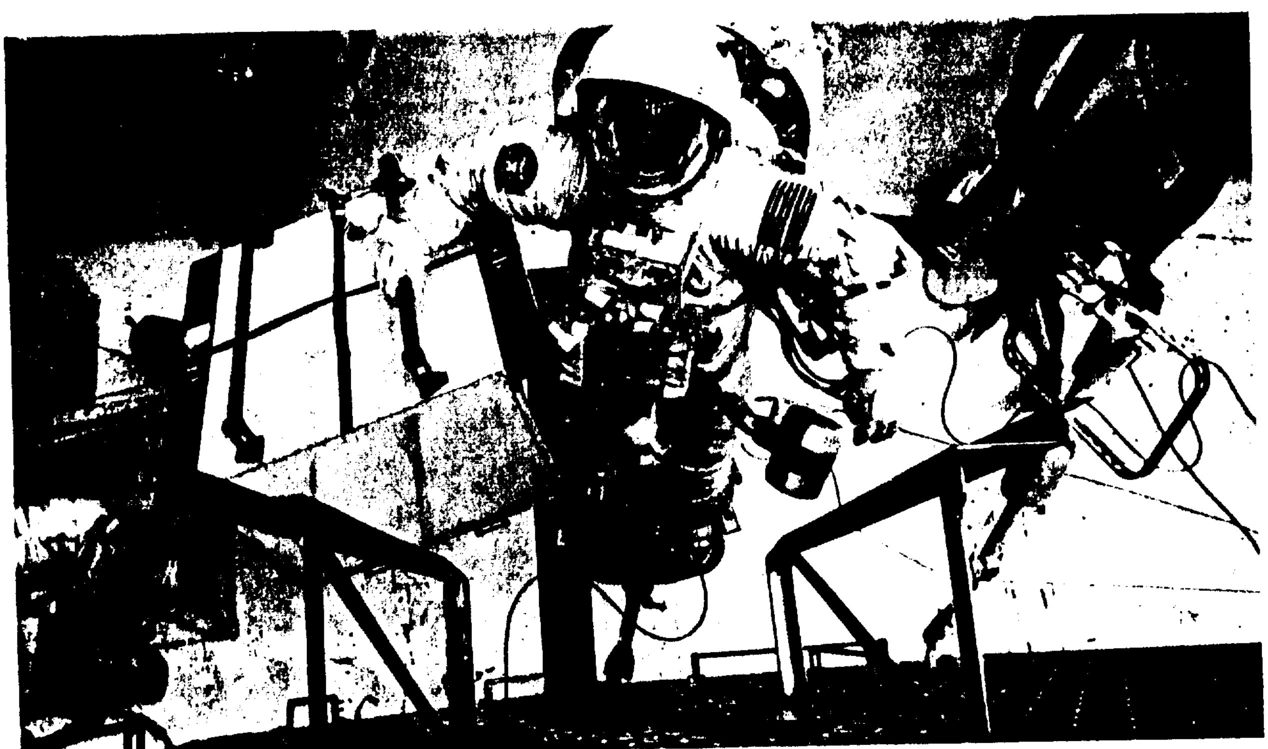

Figure F-39. EV1 is in the foot restraint, and prepares to manipulate the new ORU to the stanchion

Figure F-40. EV1 moves the replacement ORU around the installed equipment at the worksite

Figure F-41. EV1 temporarily installs the ORU on the stanchion and is now ready to begin the worksite tasks

Timeline Assessments

Many of the recurring primitive tasks detailed in the baseline timeline scenarios are related to the unique requirements of working in a microgravity environment. Figure F-42 provides a listing of the recurring tasks, their frequency during the Baseline ITA EVA Maintenance Timeline, and the total time each primitive requires during the entire EVA.

	A	B	C	D
1		AVERAGE	# IN	SUMMARY
2	TASKS	TASK TIME	TIMELINE	TIME
3				
4	Tether to and Install PFR	0:03:41	13	0:47:53
5	Tether to PFR and Remove from Socket	0:03:16	13	0:42:28
6	Transfer Object via Clothesline to Works	0:01:50	12	0:22:00
7	Remove ORU Captive Bolts	0:05:14	4	0:20:56
8	Clothesline Operations	0:02:27	8	0:19:36
9	Tether to Object	0:00:29	36	0:17:24
10	Close Door (Toolbox, PWP, & ULC)	0:02:07	8	0:16:56
11	Release Tether	0:00:21	36	0:12:36
12	Attach Object to Clothesline	0:00:45	12	0:09:00
13	Release Object from Clothesline	0:00:45	12	0:09:00
14	Ingress PFR	0:00:28	19	0:08:52
15	Egress Airlock	0:08:47	1	0:08:47
16	Open Door (Toolbox, PWP, & ULC)	0:01:02	8	0:08:16
17	Ingress Airlock	0:06:11	1	0:06:11
18	Egress PFR	0:00:09	19	0:02:51
19	Remove Tool from MWS	0:00:26	6	0:02:36
20	Get Tool from Toolbox	0:01:11	2	0:02:22
21	Install Stanchion	0:00:42	3	0:02:06
22	Unstow Clothesline	0:01:19	1	0:01:19
23	Stow Clothesline	0:01:19	1	0:01:19
24	Replace MWS in Toolbox	0:01:15	1	0:01:15
25	Close Thermal Cover/EVA Hatch	0:01:03	1	0:01:03
26	Attach MWS to EMU	0:00:52	1	0:00:52
27	EV1 Pass Object to EV2	0:00:19	2	0:00:38
28	Release MWS from EMU	0:00:25	1	0:00:25

Figure F-42

Installing and removing portable foot restraints (PFRs) is the most time-consuming task primitive. The PFR has a star-shaped probe on the end that must be inserted into a preinstalled socket. The star-shaped probe requires that proper orientation be obtained prior to installation in the socket. With the current SSF configuration, the PFR must be installed and removed from each worksite. It was assumed that the PFR must also be installed and removed from the logistics carrier.

Transferring an object via the clothesline was the second most time-consuming task primitive. The current clothesline design only has the ability to transfer one item at a time; therefore, the 12 different transfers were required. In addition, the clothesline had a tendency to tangle during the WETF tests. This problem could be increased with the effects of microgravity.

The third highest driver involved bolts on the ORU. It was assumed in this timeline that the average ORU required four bolts, which served as launch restraints in the ULC and were necessary for installation at the worksite. The average time reported included installing or removing all four bolts. The power tool was assumed to be the only tool necessary to manipulate the bolts.

The most frequent task primitive involves the use of tethers. The crew and their equipment must be securely attached at all times to the SSF structure to prevent accidental separation and recontact. Tether protocol defines the procedures used to secure the crew and their equipment. Several types of tethers are used, including waist tethers, safety tethers, and wrist tethers. Each time a tether must be used, it must first be released from its attachment point, then attached to the required equipment. Because of the frequency of tether use (72 times), the total time required was significant. Sight and dexterity limitations caused by the EMU can result in tether operations taking twice or three times as long as the average task time used in the timelines.

Ingressing foot restraints probably has the widest variation in times. Figures F-43-46 show an example of ingressing a foot restraint. The astronaut must first insert the toe of the boot in the foot restraint, then lock the heels down.

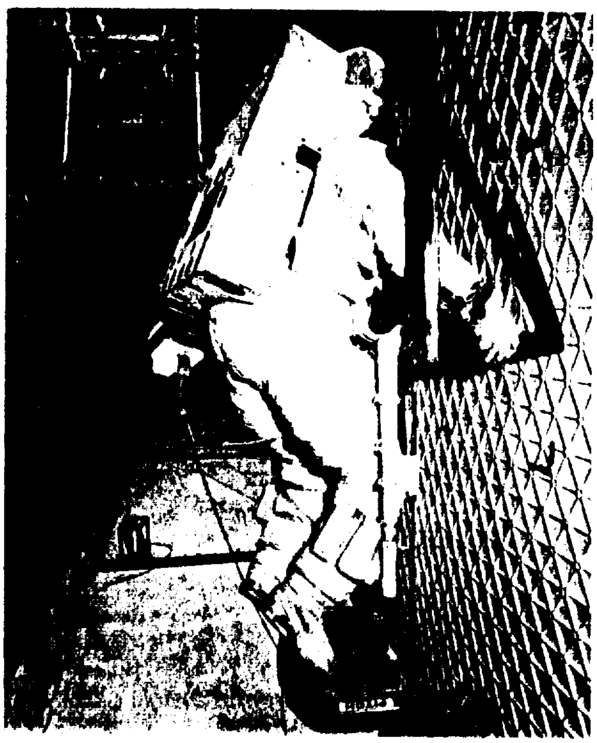

Figure F-43. Crew member uses the Space Station ORU interface as an ingress aid

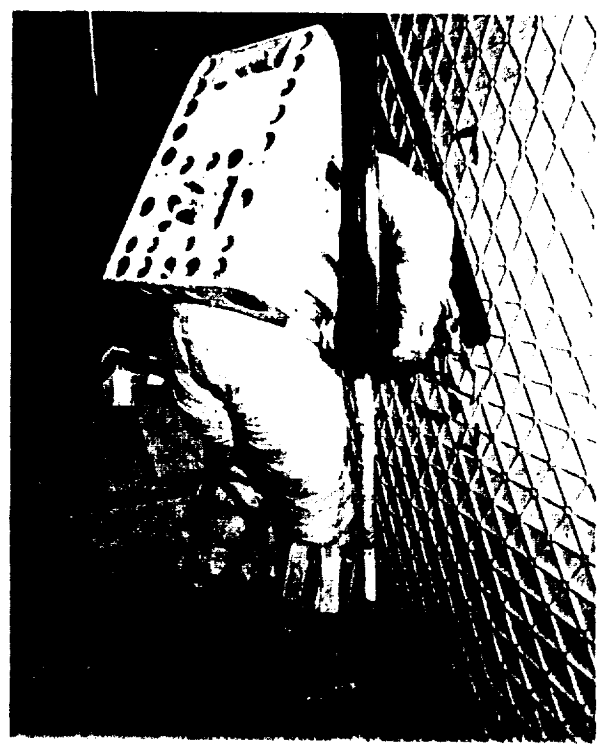

Figure F-44. Crew member places toes under the toe-holds

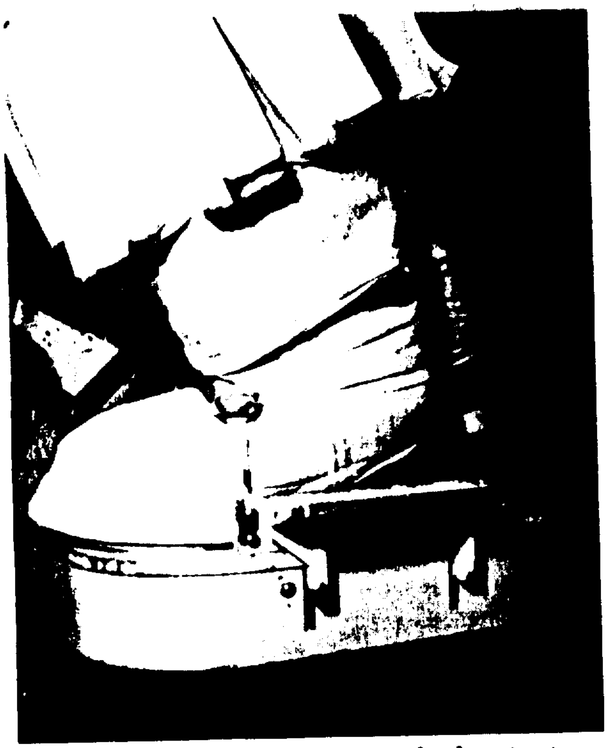

Figure F-45. Boot in foot restraint, heels not yet locked in place

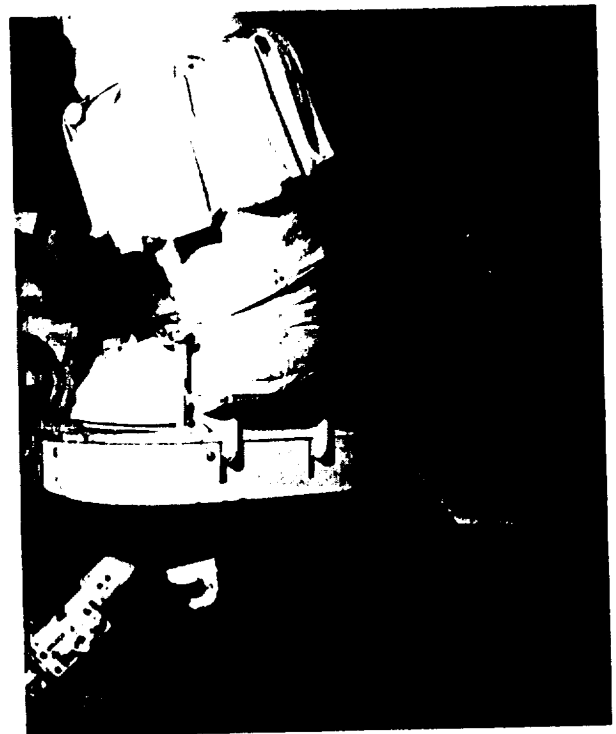

Figure F-46. Heels down and boot locked in foot restraint

"Best Case" ITA Maintenance Timeline Assumptions

The "Best Case" ITA maintenance timeline (shown in Attachment 6) indicates the procedures and task times that would occur if all equipment had been designed and optimized for efficient operation, and for use by a single EVA crew members.

The following assumptions concerning equipment design and operational requirements were used in the "best case" ITA maintenance EVA timeline:

1. Airlock egress is the same as currently baselined
2. The tools are stowed on the CETA carts
3. There are 2 CETA carts
4. The CETA rail is routed directly from the airlock to the main CETA rail such that no switching operations or CETA cart rotation is necessary
5. A PWP was installed (prior to the EVA by the robots) at the first worksite location of each crew member
6. The logistics carriers are close enough to the CETA rail so that use of a transfer device is not necessary
7. The logistics carriers have foot restraints on them
8. The CETA cart can carry three ORUs simultaneously
9. The ORUs are located in the same logistics carrier
10. No additional lighting is needed at the worksite
11. A transfer device exists with the following characteristics:
    a. Ability to transfer multiple pieces of equipment simultaneously
    b. The design has been optimized for efficient operation by 1 crew member
    c. Provides positive control of the equipment that is transferred

12. Transfer device is normally stowed on the CETA cart
13. No additional lighting is required at the worksites
14. It is not necessary to remove truss struts and other equipment in order to transfer equipment to the worksite
15. An "over center" latch or some other single-action mechanism is used as a launch restraint in the ULC, eliminating the need to remove bolts with a power tool
16. The PWPs can be left at the last worksite for the robots to put into stowage at a later time
17. No thermal conditioning is needed for the ORU between removal from the ULC and installation at the worksite
18. All tools and equipment necessary for crew members to work independently exist and have been optimized for use as such
19. Handrails, tether points, and all restraint aids exist in optimum locations
20. Short tasks such as EMU checks can be performed during the allotted worksite task time and are not necessary during performance of EVA overhead tasks
21. Six maintenance tasks exist which are 1-man 1-hour tasks
22. The logistics required to complete the tasks exist on orbit in ULCs

The "Best Case" ITA Maintenance Timeline shows that 2 crew members working independently can accomplish six 1-hour one-man worksite tasks in just under 6 hours.

"Best Case" EVA Overhead Factor

The EVA overhead factor based for the "Best Case" ITA Maintenance Timeline can be calculated as follows:

$$\text{"Best Case" EVA Overhead Factor} = \frac{(5.6\text{ hours})(2\text{ crew})}{(6\text{ hours of tasks})(1\text{ crew})} \approx 2$$

Given: Ground rules and assumptions stated in this study

It should be noted that this overhead factor is based on the assumption that 6 tasks exist which are all 1-man 1-hour tasks. This may not always be the case, as 26% of the tasks are greater than 1.1 hour, and 25% of the tasks as currently reported require 2 crew members. The average EVA overhead factor will probably be somewhat higher than 2 because of the variance in maintenance task requirements.

Because the "Best Case" EVA overhead factor was developed using the same ground rules as the Baseline EVA overhead factor, it does indicate a factor of merit achieved by improving the designs for operational efficiency.

Recommendations

During the development of the baseline timelines, it became obvious that there were many areas where the performance of EVA overhead tasks could be streamlined. The following list is a refinement of the preliminary recommendations list developed during the External Maintenance Task Team Midterm meeting in April, 1990. Note that some of the recommendations result in direct EVA overhead time savings, where others pertain to controlling overhead throughout the remaining design phase.

The following list of recommendations is in no specific order; however, design-related recommendations and programmatic-related recommendations are grouped separately.

Design-Related Recommendations

1. **Provide dual sets of EVAs support equipment (e.g., two CETA carts) to enable the two EVA crew members to complete end-to-end maintenance actions simultaneously**

   BASIS–The majority of tasks performed at a worksite can be completed by one EVA crew member. If the EVA overhead tasks are designed and optimized for one person to perform, two EVA crew members may exit the airlock together; then go their separate ways, thereby accomplishing almost twice what they could jointly. There are no flight rules preventing the two crew members from venturing far from one another. Studies have shown that, using the CETA, an astronaut can rapidly rescue the EVA partner and return that partner to the airlock in an emergency.

2. **Design the CETA ORU carrying provision to accommodate transport of multiple ORUs, and eliminate the need for crew members to make more than two trips to the ULC in an EVA (once at the beginning to acquire new units and once at the end to returned failed ones)**

   BASIS–With the current CETA and ORU attachment scheme, an EVA crew member performing multiple maintenance actions in an EVA must return to the ULC to replace and retrieve each failed and new ORU. Using the best case scenario presented in this report, a crew member on the CETA should be capable of simultaneously transporting three ORUs of maximum weight and dimensions expected for installation in this fashion. To avoid a tremendous impact on the EVA corridor and CETA rail design, this recommendation might be implemented by providing multiple CETA ORU carriers linked in the manner of railroad box cars.

3. **Design the CETA rail for direct routing to the airlock from either direction on the transverse boom without the operation of the airlock or alpha joint switching mechanisms**

   BASIS–Overhead time associated with operation of these mechanisms can be eliminated completely by routing the CETA rail appropriately. For example, a "circular drive" CETA rail at the airlock would permit direct translation past the airlock from either side of the transverse boom without a spur mechanism. Routing the CETA rail external to the truss structure or through the center of the alpha joints, for example, would eliminate the dual rail rotation mechanism. Obviously, these alternatives have impacts. A circular drive at the airlock is likely to have greater mass than the current spur. Allowing an exterior EVA corridor beyond the alpha joints necessitates relieving the requirement to keep the corridor interior to the truss. Similarly, routing the CETA rail through the alpha joints requires a new alpha joint design. However, the one-time impact of these changes may be overshadowed by recurring savings over the lifetime of the station. Elimination of these mechanisms would additionally enhance crew safety and avoid stringent reliability requirements imposed on any mechanism that stands between the EVA crew and their airlock.

4. **Provide the capability to store and relocate the PWP components on orbit in any configuration of partial or complete assembly**

   BASIS–If the PWP is used for EVA maintenance as often as currently envisioned, whether stationary at a worksite or on the end of the SSRMS, the EVA crew should be able to stow it without disassembly between EVAs. For example, if the PWP is almost always used with the light stanchion in place, it should be designed to be stowed and transported so configured.

5. **Design the PWS components for long-term exposure and eliminate the PWSs**

   BASIS –Accessing a component from the PWS and replacing it at the end of the EVA is overhead which can be avoided by designing the contents for long-term exposure. This may be optimistic for powered tools and equipment but should have little impact on the design of simple structures and mechanisms.

6. **Provide the capability to stow one PWP on each CETA and the third on the Mobile Servicing System's MBS**

   BASIS–The PWPs are generally not used on the airlock but rather transferred to the CETA, stowed, and transported to the worksite for any maintenance action performed on the ITA. Similarly, when the PWP is used on the SSRMS, it must be retrieved from the airlock, stowed on the CETA, transported to the worksite and the waiting SSMRS, and mounted. (If the PWP were mounted on the SSRMS at the airlock, EVA time would be wasted while the MT subsequently moved to the appropriate truss bay.) Stowing a PWP on each CETA and the MBS creates two more overhead tasks for maintenance actions on the module pattern. Conversely, it eliminates several of the overhead steps normally involved in support equipment setup and cleanup for most maintenance EVAs.

7. **Provide the capability to stow a PWP on the MBS in such a way that it can be deployed onto the SSRMS or installed at a worksite, and returned to the MBS by the SSRMS**

   BASIS–Additional EVA overhead steps can be avoided with the appropriate design of the PWP stowage on the SSRMS. A stowage mechanism that allows the SSRMS to pick up and return the PWP without EVA assistance saves the same EVA operations. A PWP configuration which additionally allows the SSRMS to mount the PWP on a pallet or other worksite location saves EVA setup and transfer of the PWP to/from the CETA.

8. **Provide for storage of one set of tools on each CETA cart**

   BASIS–EVA tools generally are not used on the airlock but rather retrieved and transported to the worksite. Stowage of tools on CETA "box cars" not only significantly reduces the need to transport them from the airlock but also ensures that all commonly used tools are available at the worksite. Having a selection of tools in close proximity may be particularly helpful in cases where corrective measures are uncertain before a first-hand EVA inspection.

9. **Locate the CETA rail and the ULCs in proximity to one another. Consider designing them in such a way as to enable EVA retrieval and replacement of ORU's without leaving the CETA PFRs**

   BASIS–The transfer of an ORU from the ULC to the CETA is as time-consuming as the transfer from the CETA to a pallet. The former procedure could be simplified, however, by locating and designing the ULCs and the CETA in a complementary manner. Such a "drive-in" ULC concept could be satisfied by rerouting of the CETA rail or strategic placement of the ULCs. This recommendation may impose requirements on the design of both elements. The least impact approach may entail placing all ULCs on the aft station face and making ORUs accessible from the inside of this face. In this way, ORUs might be retrieved from beneath the CETA rail.

10. **Provide dedicated PFRs at all sites frequently visited by the EVA crew (e.g., worksites with low MTBFs)**

    BASIS–Such restraints could be launched in place or, alternatively, manifested as margin permits and left in place the first time the EVA crew visits the worksite.

11. **Provide dual sets of dedicated PFRs at sites where crew members are likely to be working simultaneously while performing independent maintenance activities (e.g., ULC subcarrier berthing mechanisms)**

    BASIS–This recommendation could prevent unexpected overhead in the case where the two crew members work independently by eliminating the need for one person to wait until the other has finished his/her task at a particular location.

12. **Provide spare PFRs to enable the crew to leave them in areas with a high concentration of ORUs (e.g., each pallet), at sites which will be visited again soon, or in any location that is found to warrant a dedicated PFR**

    BASIS–Ideally, the station EVAs should, over time, provide enough foot restraints that a PFR need not be removed once installed at a worksite. In the meantime, one PFR per pallet, for example, may be adequate to significantly reduce the overhead of acquiring and transporting PFRs. It is prudent to expect that we will not know where dedicated foot restraints are needed in the beginning, so there should be extras to accommodate EVAs evolving needs.

13. **Investigate potential redesigns or improvements to existing PFR sockets, wrist tethers, and other frequently used EVAs support equipment to improve operational efficiency**

    BASIS–Tolerances on PFR sockets and the method of operating tether hooks are two features of existing orbiter EVA hardware that potentially could be improved. These items and others are currently proposed for use on SSF without modification.

14. **Provide an equipment transfer device which enables:**

    a. **simultaneous transfer of ORUs and support equipment to/from a worksite in a single deployment**

    b. **efficient operation by a single, unaided EVA crew member**

    c. **positive control of all objects during transfer operations to prevent inadvertent bumping of equipment**

BASIS–Transfering multiple objects at once on the equipment transfer device is necessary to support independent crew operations. Such a capability would preclude extra trips between the CETA and the worksite. In addition, EMTT WETF test results indicated that positive control of equipment during transfer is needed to prevent damage to the equipment or surrounding structures. During testing, items flailed about on the clothesline. Crew members speculated that this movement would be more pronounced on orbit without the aid of water drag. A device such as a bistem extender like that used to deploy the Assembly Work Platform on MB-1 might satisfy all explicit and derived requirements of this system.

15. **Minimize the number and complexity of ORU restraints required for transport in the ULC, removal/replacement in the ULC, attachment to the CETA, and installation at the worksite**

    BASIS–Bolts need not be the only form of permanent or temporary restraint of an ORU. The benefits of quick connect/disconnect attachments can be realized in the reduction of both EVA overhead and worksite task time.

16. **Investigate telerobotic applications for selected EVA overhead primitive tasks before and after the EVA occurs to directly eliminate the need to do these operations EVA**

    BASIS–Any task preparation or closeout tasks, such as transport of the ORU to/from the worksite, which can be completed end-to-end by a telerobotic system directly reduces EVA overhead. Impacts to IV maintenance time must be considered in any assignment of tasks to telerobotics.

17. **Provide tether points to accommodate attachment of two tethers simultaneously on all equipment which the EVA crew must transfer, hand off, or temporarily stow using tethers. Locate the tether points as closely as practicable to the object's c.g.**

    BASIS–When an EVA crew member follows proper tether protocol, an object must be secured, either to another object or to another tether, before the crew member may remove his/her tether. Current EVA overhead tasks occasionally require that a second tether, such as one from the clothesline, be attached to an item before the handling tether is removed. This necessitates either two regular tether points or one large tether point that will accommodate the attachment of two tethers. To simplify handling and alleviate equipment rotation during transfer, it is preferable to place these points near the object's c.g. Note that the c.g. is beyond crew reach.

Program-Related Recommendations

1. **Implement a programmatic requirements change to ensure that all EVA tasks will be optimized for performance by one EVA crew member**

   BASIS–Designing and optimizing all EVA overhead tasks for one EVA crew member is the single most productive step discovered in this study for reducing the EVA overhead factor. Since 75% of all worksite tasks are already proposed for one EVA crew member, this change would enable simultaneous, independent EVA operations on the majority of station maintenance EVAs.

2. **Replace the CSA provided MFR and its stowage on the MBS with stowage provisions for a PWP which can accommodate unassisted deployment, installation, and stowage by the SSRMS**

   BASIS–A PWP is essentially a new and improved version of the MFR. This makes the CSA MFR an unnecessary piece of station hardware. In addition, the present-day MFR requires EVA to deploy it from the orbiter, attach it to the RMS, and subsequently remove and stow it. With the implementation of design recommendation number 7, the station crew will be able to preposition a PWP before the EVA.

3. **Implement programmatic directions to ensure a proper balance of development and operational considerations in design decisions**

   BASIS–With the emphasis to meet weight, cost, power, and volume allocations and other tangible requirements, long-term operational efficiency can be overlooked in the design process. Often, the least-volume and lowest-weight design concept functions, but severely hampers operations. A variety of steps should be taken to balance engineering and operational considerations including a programmatic weighting system for use in future trade studies and joint operations/development roles in working groups and other forums.

Concluding Remarks

This study has shown that individual designs can have great influence on the total crew time required to perform external maintenance. With the current baseline equipment designs and configurations, EVA overhead is the major driver in the number of EVAs required to meet annual external maintenance requirements.

The "Best Case" Timeline indicates that operational efficiency can be tripled if all of the equipment that affects EVA overhead tasks are optimized for operational efficiency.

Current baseline designs are not as operationally efficient as they could be due to individual trade studies that are performed on each design. During the design phase, equipment designs are compared based on weight, cost, volume, power requirements, and crew time requirements. Traditionally, lowest weight, cost, and volume have been the drivers in design decisions. The SSF, though, is a unique program. It is designed for 30 years of operation in space, but more importantly, it must be maintained in space by astronauts, and crew time is a valuable resource.

Design cost, weight, and volume are critical factors; however, design cost is a one-time cost. Weight and volume are critical because of the launch constraints, but for high reliability items, these costs are incurred infrequently. The cost of operating inefficient equipment is incurred every time equipment is used. During a 30-year program, these costs can outweigh the differences in the other factors; therefore, more emphasis must be placed on designing operationally efficient equipment.

Implementing the design-related recommendations detailed in this report will increase the operational efficiency of the current design. It is critical, though, to establish a balance between weight, cost, volume, and lifetime operational expense for future phases of the SSF Program. Program direction will be necessary to ensure that a proper balance of these elements is established and implemented into all trade studies.

Acknowledgments

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- All personnel at the Weightless Environment Training Facility at JSC.
- Astronaut test subjects, David Leestma, G. David Lowe, Jerry Ross, Tammy Jernigan, Linda Godwin, and Mike Foale, who participated in the WETF tests.
- The personnel at JSC's Photography and Television Technology Division.
- All personnel who participated in the mid-term splinter group meeting.
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- Mission Operations Directorate personnel, Karen Archard, and Charles Armstrong, who provided an exceptional amount of support to this study.
- All additional personnel who provided information and support to this study.

Bibliography

"EVA Overhead Factor," presentation to the Resource Allocation and Functional Partitioning Panel (RA&FP), October 1989.

"EVAs Preliminary Design Review Presentation," presentation at the EVAs summary PDR presentations, June 1989.

Appendix F

Attachment 1

EVA Overhead Task Time
WETF Test Plan

May 21 and 22, 1990

Sponsored by,
External Maintenance Task Team
(EMTT)

Laura L. Janicik
and
LeBarian Stokes

Coordinated by,
Mission Operations Directorate

Karen Archard

Introduction

This test will serve three purposes:

a. To obtain EVA overhead task timeline information that can be used in final report of the External Maintenance Task Team's

b. To obtain still photographs of individual overhead tasks and video footage that can be reproduced in the final report

c. To evaluate the consensus strawman "box-type" ORU concept developed by the EMTT, along with representatives from each work package and international partner. The primary focus of this test run will be an evaluation of the compatibility of the design standards with the EVA crewman

The test setup will be similar in design to a portion of the "Access to an Interior-Mounted Pallet and ORUs" which was run in August of 1989; however, the purpose and objectives are very different.

The emphasis of this test is to simulate an ORU changeout from airlock egress to airlock ingress, simulating operations in a true space environment as closely as possible. Individual task times will be extracted and used to qualify an "EVA Overhead Factor" prediction. It should be noted that while this test is being used to obtain timeline information, there is not necessarily a correlation between the entire test time and the time required for an actual EVA task.

Suited personnel involved in the test will be requested to adhere strictly to all rules and tether protocols followed in an actual EVA. Safety and utility divers will be requested to minimize providing assistance to the crew, except in instances where safety concerns exist.

This test is being coordinated by Mission Operations Directorate Personnel for the External Maintenance Task Team. Class III suit and ancillary equipment support has been requested from Johnson Space Center's (JSC) Crew and Thermal Systems Division. The test will be conducted in JSC's Weightless Environment Training Facility in May, 1990. Test subject comments concerning the ORU and the test procedures will be obtained during the exercise.

The measurements and issues to be addressed include the following:

A. The average time to
   1. Egress the airlock
   2. Attach the Mini Work-Station (MWS) to the EMU
   3. Attach tools to the MWS
   4. Ingress CETA PFRs
   5. Translate on the CETA
   6. Translate to an outer-face pallet
   7. Set up the clothesline device
   8. Attach and remove items from the clothesline
   9. Transfer items from the CETA to the worksite using the clothesline
   10. Install a PFR and stanchion at the worksite
   11. Attach an ORU to temporary stowage at the worksite
   12. Install and remove an ORU

B. An evaluation of the following:
   1. The overall acceptability of the strawman box-type ORU design
   2. Compatibility of the ORU design standards as applicable to EVA operations, including
      a. Fastener type
      b. Clearance around the fastener
      c. Bolt head sizes
      d. Interfaces (man-ORU, tool-ORU,ORU-structure)
      e. Kinematic motion
      f. Alignment guides
      g. Visual Cues
      h. Box size
      i. Status indicators
      j. Soft Dock mechanism

See Attachment 3 for further details

3. Interference in transferring equipment on the clothesline

4. Ways to streamline EVA Overhead Tasks

Test Philosophy

Neutral buoyancy simulations have been used extensively to both develop and master EVA procedures by negating some of the effects of gravity and permitting crew members to perform EVA operations as they would on orbit. Although underwater motion by humans and mechanisms is opposed by drag which is virtually nonexistent in space, such experimentation has been successful in providing a predictable correlation to orbital operations. This test will make use of that correlation to provide incremental timeline information, provide information useful in driving design requirements, and allowing real-time assessments of procedure performance.

To ensure the accuracy of each simulationperformance, the guidelines for test mockups and proper test conduct will be consistent for all simulations:

- All procedures and hardware will be generated to approximate baselined on-orbit operations as closely as possible
- Test requirements will include the accurate collection of timed audio and video coverage of test activities
- Prior to WETF testing, all test requirements and operations will be reviewed and approved by the NASA Test and Readiness Review Board
- An all-hands meeting consisting of personnel conducting the test, suited test subjects, and all supporting personnel will be held prior to the test runs to review the test objectives

Test Operations

Hardware Description and Test Setup

The simulated SSF structure will consist of the Space Shuttle airlock, three assembled bays of five-meter truss, utility trays, CETA rails, a CETA cart with ORU carrying capability, safety tethers from the airlock to the CETA, and a pallet (see figure 1). The airlock will be placed on the floor of the WETF and will serve as the starting point for the test. The fidelity of the airlock does not affect this test, so the Shuttle airlock was selected to minimize WETF preparation requirements.

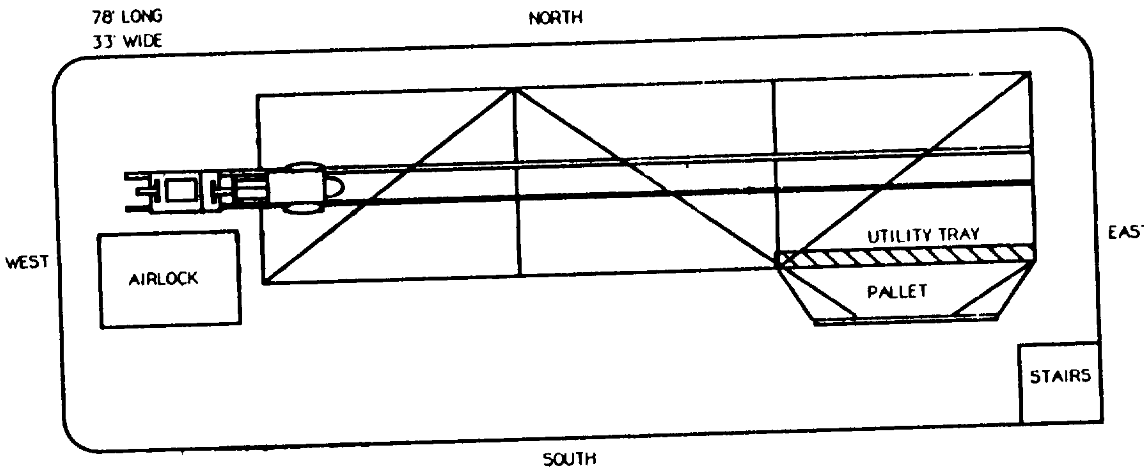

Figure 1. WETF Test Setup - Top View

Three assembled bays of truss will sit on supports above the WETF floor to allow for realistic placement of the CETA rail (see figure 2). The CETA rail will be centered on the lower inner face of the truss bay. At the start of the test, the CETA cart will be located on the slide rail at the end of the truss bay nearest the airlock.

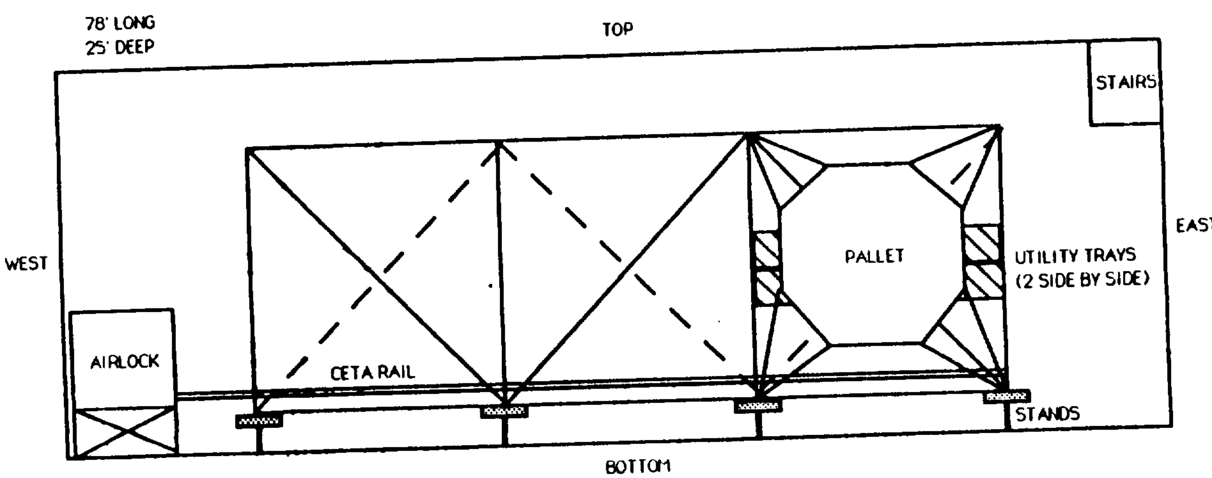

Figure 2. WETF Test Setup - Side View

The CETA cart will be configured prior to the start of the test with the following equipment installed: 2 portable foot restraints (PFRs) installed in two sockets, a clothesline device, and safety tethers initially routed to the airlock. The CETA will have the following equipment stowed for later removal during the test: the test subject ORU sized 36"x38"x18," the neutrally buoyant PFR, and stanchion (used to simulate the baselined portable work platform (PWP)). The regular HST PFR should be available to the divers for exchange during the test.

A pallet will be attached to the outer side face of the truss bay farthest from the airlock. The pallet will be equipped with a regular PFR socket to hold the PFR and an articulating PFR socket to hold the tool stanchion. The attachment jig for the ORU will be located on the pallet at an appropriate distance to facilitate access by all suited test subjects while ingressed in the PFR.

Two utility trays (with handrails on inner sides removed) will be located side by side on the inner face of the same truss bay side containing the pallet. This will accurately simulate SSF configuration and will provide realistic interferences during ORU transfer operations.

<u>Test Procedure</u>

See Attachment A

<u>Data Evaluation</u>

The following data recording is necessary for this test:

- Still photographs showing detailed sequences, configurations at specific test points, and general overviews (a detailed listing is shown in the "photographs" column of Attachment 1). Black and white film is required so that the pictures can be reproduced in the External Maintenance Task Team Final Report.
- Dual video and audio recording with Greenwich Mean time notation. The audio/video recordings are requested in both 3/4" and 1/2" formats in order to provide maximum resolution for editing and to provide viewing flexibility for extraction of timeline data.

All data gathered will be correlated and used to support the findings and recommendations that will be included in the External Maintenance Task Team Final Report to be submitted by July 2, 1990.

	A	B	C	D
1	TASKS	PROJECTED TIMES	ASSUMPTIONS	PHOTOGRAPH
2				
3				
4	EV2 secure left waist tether to airlock	0:01:00	2 crewmen req'd for EVA	
5	EV1 secure right waist tether to EV2s right waist tether	0:01:00		
6	Open EVA hatch	0:01:00		
7	EV1 exit airlock	0:00:15		
8	EV1 secure L w-tether to CETA safety tether D-ring #1	0:00:30	Safety tethers secured to CETA	
9	EV1 unhook EV2's R waist tether & attach to D-ring #2	0:01:00	Reel cases routed to airlock	wide angle
10	EV2 unhook left waist tether	0:01:00		
11	EV2 exit airlock	0:00:15		
12	Remove safety tethers from pouches	0:01:00	Reel cases stowed - soft carry pouch	
13	Unlock safety tethers	0:00:10		
14	Follow safety tether lines to CETA & release restraints	0:02:00	Restraints req'd for line mgmt	
15				
16				
17	Translate to tools	0:00:15	Tools on airlock floor	Close sequence
18	Tether to HST Semi-Rigid Tether	0:01:00		close
19	Attach HST Semi-rigid Tether to EMU	0:01:30		
20	Release Tether	0:00:30		close
21	Tether to Mini Workstations	0:00:30		close
22	Attach MWS to EMU	0:01:30		close
23	Release tether	0:00:30		
24	Tether to tool caddy	0:00:30		
25	Attach tool caddy to MWs	0:00:30		
26	Release tether	0:00:30		
27	Tether to 2nd tool caddy	0:00:30		mid
28	Attach tool caddy to MWS	0:01:00		
29	Release tether	0:01:00		
30	EV1 tether to tool using MWS retractable tether	0:00:30		
31				
32	TIMEOUT FOR BALLASTING !!!!!			
33				
34	Translate to CETA	0:00:15		wide angle
35	EV1 and EV2 ingress CETA PFRs	0:01:00	PFRs both facing east	
36	Translate on CETA to east maintenance worksite	0:01:00	Divers predetermine best stop point	close sequence
37	EV1 egress PFR	0:00:30		close sequence
38	EV1 attach HST NB foot restraint to HST SRT	0:01:00		
39	Rigidize HST SRT	0:00:10		
40	Release NB foot restraint from CETA	0:00:30		mid
41	Tether to clothes line end	0:01:00		
42	Translate along truss to worksite	0:01:00		
43	Release clothesline tether & attach to pallet	0:01:00	Handrail there on pallet w/tether pt	
44	Derigidize tether	0:00:10		close sequence
45	Install PWP PFR in socket and adjust position	0:01:30		
46	Release HST SRT from PFR	0:00:30		
47				
48	TIMEOUT - DIVERS TRADE HST PFRs			
49				
50	EV2 tether to PWP stanchion	0:00:00	Done in parallel with EV1 tasks	
51	Release stanchion from CETA	0:00:00	Done in parallel with EV1 tasks	
52	Attach stanchion to clothesline hook	0:00:00	Done in parallel with EV1 tasks	
53	Release tether	0:00:00	Done in parallel with EV1 tasks	
54	Transfer stanchion to worksite	0:00:00	Done in parallel with EV1 tasks	wide angle
55	EV1 tether to stanchion	0:00:30		close
56	Release stanchion from clothesline	0:00:30		close
57	Install stanchion	0:01:30		mid
58	Release tether	0:00:30		
59	EV2 transfer clothesline hook to CETA	0:00:30		wide
60	EV2 tether to ORU	0:00:00	Done in parallel with EV1 tasks	mid
61	Release ORU from CETA	0:00:00	Done in parallel with EV1 tasks	close
62	Attach ORU to clothesline hook	0:00:00	Done in parallel with EV1 tasks	mid
63	Release tether	0:00:00	Done in parallel with EV1 tasks	mid
64	Tranfer ORU to worksite	0:02:00		wide
65	EV1 tether to ORU	0:00:30		close
66	Release ORU from clothesline	0:00:30		close
67	Attach ORU to stanchion	0:01:30		close
68	Release tether	0:01:00		close
69	Ingress PFR	0:01:00		close sequence
70				
71	Tether to new ORU	0:00:30		
72	Release ORU from stanchion	0:00:30		close
73	Attach ORU to pallet	0:00:30		mid
74	Remove power tool from MWS	0:00:10		
75	Install two bolts	0:04:00	BLUE BOLT FIRST - OTHER IS FAKE	close
76	Release tether	0:01:00		
77	EV1 tether to failed ORU	0:01:00		
78	Remove power tool from MWS	0:00:10		
79	Remove two bolts	0:04:00		mid
80	Release ORU from pallet	0:00:30		mid
81	Attach ORU to stanchion	0:00:30		
82	Release tether	0:00:30		

	A	B	C	D
83				
84	EV1 egress PWP PFR	0:00:30		
85	Tether to failed ORU	0:01:00		
86	Release ORU from PWP	0:00:45		
87	Attach ORU to clothesline hook	0:00:30		
88	Release tether	0:01:00		mid
89	EV2 transfer ORU back to CETA	0:02:00	Clear path from worksite to CETA	wide
90	Tether to ORU	0:01:00		
91	Release ORU from clothesline	0:00:30		
92	Attach ORU to CETA	0:01:30		
93	Release tether	0:01:00		mid
94	EV2 transfer hook to worksite	0:00:30		
95	EV1 tether to stanchion	0:00:00	Done in parallel with EV2 tasks	close
96	Release stanchion from foot restraint	0:00:00	Done in parallel with EV2 tasks	close
97	Attach stanchion to clothesline hook	0:00:00	Done in parallel with EV2 tasks	close
98	Release tether	0:00:00	Done in parallel with EV2 tasks	close
99	EV2 transfer stanchion to CETA	0:02:00		wide
100	Tether to stanchion	0:01:00		
101	Remove stanchion from clothesline hook	0:00:30		
102	Attach stanchion to CETA	0:01:30		
103	Remove tether	0:01:00		
104				
105	TIMEOUT - DIVERS SWITCH PFRs			
106				
107	EV1 use HST SRT to tether PFR	0:00:00	Done in parallel with EV2 tasks	
108	Remove PFR from socket	0:00:00	Done in parallel with EV2 tasks	close
109	Rigidize HST SRT	0:00:10		
110	Release clothesline & attach to tether	0:00:00	Done in parallel with EV2 tasks	mid
111	Translate to CETA	0:00:00	Done in parallel with EV2 tasks	wide
112	Release clothesline tether & stow on CETA	0:00:00	Done in parallel with EV2 tasks	
113	Attach PFR to CETA	0:00:00	Done in parallel with EV2 tasks	
114	Remove tether	0:01:00		
115	EV1 and EV2 ingress PFRs	0:01:00		
116				
117				
118	Translate to airlock	0:01:00		wide
119				
120				
121	Translate to tool area	0:01:00	EV1 and EV2 working in parallel	
122	Release tool from MWS	0:00:15		
123	Replace power tool on floor	0:00:20		
124	Release MWS retractable tether	0:00:30		
125	Tether to Tool Caddy	0:00:30		
126	Release tool caddy from MWS	0:00:10		
127	Place on floor	0:00:10		
128	Release tether	0:00:30		
129	Tether to 2nd tool caddy	0:00:30		
130	Release from MWS	0:00:10		
131	Place on floor	0:00:10		
132	Release tether	0:00:30		
133	Tether to MWS	0:00:30		
134	Release MWS from EMU	0:00:30		
135	Replace MWS on WETF floor	0:00:20		
136	Release tether	0:00:30		
137	Tether to HST SRT	0:00:30		
138	Release SRT from EMU	0:00:10		
139	Place on floor	0:00:10		
140	Release tether	0:01:00		
141				
142	TIMEOUT FOR RE-BALLAST IIII			
143				
144	Translate to CETA	0:01:00		
145	Route safety tether lines to airlock & engage line restrain	0:02:00		
146	Lock safety tethers	0:00:10		
147	Replace safety tethers in pouches	0:01:00		
148	EV2 enter airlock	0:00:15		
149	EV2 secure left waist tether to airlock	0:01:00		
150	EV1 unhook EV2s R waist tether & attach to EV1 R tether	0:01:00		
151	EV1 unhook left waist tether	0:01:00		
152	EV1 enter airlock	0:00:15		
153	Close EVA hatch	0:01:00		
154				
155				
156	***PROJECTED TOTAL TEST TIME *********	1:28:50		
157				
158				
159				
160				
161				
162				
163				
164				

(Attachment B)

Design Standards for "BOX TYPE" ORUs to be Analyzed in May 21-22 WETF Test

All standards will be verified through further engineering analysis and testing.

#1 Fastener Types

- Captive threaded with locking feature as required

#2 Clearance around a fastener (Tool around a bolt)

- The final design requirement will place all fasteners at the same height above the box. The range being considered is ±1 inch from the surface
- Side clearance will conform to MSIS NASA Standard 3000 section 14.3.2.5 (c)

  1. When only tool access is required, a 2.5 cm (1.0 in.) minimum clearance should be provided around the fastener or drive stud for insertion, actuation, and removal of the drive end of the tool
  2. A minimum of 7.6 cm (3.0 in) should be provided for clearance between a tool handle engaged on a fastener or drive stud and the nearest piece of hardware. The tool handle should maintain this clearance through a full 180-degree sweep envelope

These specifications are illustrated in the attached drawing.

#3 Bolt Head Sizes

- 7/16" double height EVA Hex.Head as defined in the EVA Tool Catalog with the addition of an internal Hex Key interface

#4 Interfaces

- All must accept the same tool, have tool hard dock, torque reaction capability, and tool alignment
- Handling points will add capability and a visual indication that it is a handling point
- The attachment will be flush with the surface of the ORU

#5 Kinematic Motion

TOOL to ORU

- All fastening will be done in a clockwise direction
- Robot and EVA motion for connection will be in only one axis
  ORU to STATION
- Soft Dock insertion will be done with single access translation

#6 Alignment Guides

TOOL to ORU

- ± .5 in. linear alignment guide

ORU to STATION

- Determined from the graph produced by NASA Goddard in the 3/8" range. 3/4" ranged based on the ORU box size (see enclosed graph)

#7 Visual Cue

- Two dimensional target

#8 Box sizes

Standard-mount type

- Fixed width with various classes
- Incremental depth to a maximum depth
- Incremental lengths to a maximum picking up bolts at standard lengths

#9 Status Indicators

- Standard indicator clearly visible to the work system at the worksite indicating soft dock and hard dock (electrical and fluid connectors fully seated, clod plates properly installed) for both insertion and removal

#10 Soft Dock (ORU to STATION)

- Soft dock is required on all ORUs with a 5 lb linear insertion and removal force
- The soft dock mechanism will position ORUs for fastener and connector alignment
- The soft dock operation will be completed prior to the engagement of any connectors or threaded fasteners

HAZARD ANALYSIS REPORT

FACILITY: WETF

TEST TITLE: SPACE STATION EVA MAINTENANCE OVERHEAD TASKS

PREPARED BY: L. P. Matranga for "Access to pallets from a Crew & Equip Translation Aid" - Aug. 15, 1989
Modified for this test by L. L. Janicik

DATE: MAY 19,1990

HAZARD	CAUSE/ FAIL MODE	1. Personnel 2. Test Hardware 3. GSE 4. Facility 5. Other Ground Ops	HAZARD LEVEL	ASSESSMENT CONTROL	DISPOSITION TRACKING STATUS
1. Test subjects umbilicals could become entangled on mockups	Failure to adequately monitor crew translation around mockups	1. Yes 2. Yes 3. No 4. Yes 5. No	Critical	Safety divers should take all precautions to prevent entanglement	
2. Diver injury from cut, EMU damage, puncture or tear	Sharp edges on test hardware	1. Yes 2. No 3. No 4. No 5. No	Controlled	A sharp edge inspection will be performed prior to testing	
3. Diver pinching fingers between the rail and the cart	Diver holding onto rail during CETA operation	1. Yes 2. No 3. No 4. No 5. No	Critical	Minimal chance of occurrence. Instruct divers to stay clear of rail during translation	
4. Test subjects could back cart off end of rail during translation	Operation of CETA in vicinity of rail ends	1. Yes 2. Yes 3. No 4. Yes 5. No	Controlled	Attach stops at end of rails	
5. Test subjects pinch fingers between ORU and attachment points on CETA and pallet	Handling ORU boxes on sides instead of using handrails	1. Yes 2. No 3. No 4. No 5. No	Controlled	Test subjects will be instructed to use handholds when maneuvering boxes	

HAZARD ANALYSIS REPORT - cont'd

6. Subject or diver could catch fingers in gaps of rails	Hands near rail ends during manual translation	1. Yes 2. No 3. No 4. No 5. No	Critical	Personnel will be instructed to avoid these areas	
7. Pinch hazard for divers and crew operating PFR (if needed)	Hands near EMU boot and PFR mechanism	1. Yes 2. No 3. No 4. No 5. No	Critical	Personnel will be instructed to stay clear of mechanisms	
8. Pinch hazard for divers and crew operating power tool	Fingers near end of tool when attaching tool to box	1. Yes 2. No 3. No 4. No 5. No	Critical	Personnel will be instructed in proper use of power tool	

EVA Overhead Task Time Test Report

May 21 and 22, 1990

Sponsored by
External Maintenance Task Team
(EMTT)

Laura L. Janicik
and
LeBarian Stokes

Coordinated by
Mission Operation Directorate
Karen Archard

Introduction

This report presents a summary of the EVA overhead task time tests performed in the Weightless Environment Training Facility (WETF) on May 21 and 22, 1990. A full description of the test purposes, testing philosophy, mockup hardware, test setup, and procedures is contained in the test plan which accompanies this report.

In brief, this exercise was performed to gain EVA overhead task timeline information, obtain photographs of overhead tasks, and evaluate a strawman "box-type" ORU. The test setup included an airlock, a Crew and Equipment Translation Aid (CETA) rail and cart, a pallet, a Hubble Space Telescope (HST) portable foot restraint (PFR), a PFR workstation stanchion, and the ORU. The CETA traversed three bays of simulated SSF truss structure. The pallet was mounted externally to the truss and is typical of the majority of station resource or payload pallets. Provisions to install the PFR, stanchion, and ORU were preinstalled on the pallet in appropriate locations; acquisition and proper stowage of these items on the CETA were not simulated in this exercise.

Six EVA-proficient astronauts served in teams of two as subjects for the three WETF tests. They followed a set of flight-like procedures to egress the airlock, acquire tools, translate through truss structure on the Crew and Equipment Translation Aid (CETA) cart, set up the clothesline device, transfer equipment to the pallet worksite, and remove and replace an ORU. The procedures were performed three times in each test. Photographs and crew comments were collected during the first run, which also functioned as a familiarization exercise. Timeline data was collected during the second and third runs, between which the crew members switched places. Test subjects were requested to adhere strictly to proper tether protocol and call a "time out" when they encountered a test specific phenomenon.

Results and Discussion

Test subjects were able to perform all overhead and ORU removal and replacement operations but felt there were many ways to reduce EVA maintenance time. Placing EVA serviceable items on the inside of exterior pallets was one suggestion. Providing ample PFRs so that one could be installed at a worksite and left in place for subsequent visits was another.

Crew members noted several factors which could significantly affect the timeline data gathered in this exercise. One person felt that training could reduce times by a factor of two, citing a steep learning curve for techniques associated with similar station maintenance tasks. Most crew members expressed the opinion that the overhead tasks could be completed by one person. However, since pairs of crew worked together to accomplish many of the overhead tasks such as clothesline operation and stanchion installation, it was pointed out that extra time would be required for single-man operations.

Many of the test subjects' suggestions were modifications of current designs and procedures. Although the primary purposes of this test did not include soliciting design developmental ideas, many of the comments, if implemented, could affect maintenance times. Thus, certain design comments are included as they pertain to improving the operational efficiency of maintenance EVAs and by reducing EVA overhead.

Tools and Tethers

Upon egressing the airlock, the crew members donned semirigid tethers and mini workstations (MWSs) and attached two tool caddies each. The test subject who was going to perform the ORU changeout task for that particular test run also acquired an EVA power tool and required two wrist tethers to perform the overhead tasks.

The semirigid tether was intended to carry the HST PFR to the pallet, thus avoiding an extra transfer operation with the clothesline. However, crew members during the first day of testing discovered that translating along the truss struts and to the pallet surface with the PFR attached to them was an encumbrance. Thereafter, the crew dispensed with the semirigid tether.

Some difficulties were encountered with the 55-ft safety tethers.used in the test. Most crew members commented that they would rather use 35-ft tethers, as the 55-ft ones failed to retract properly. In addition, a wrist tether failed during one test run. Crew members queried did not feel that the tether failures affected the test.

MWSs and tool caddies are proposed for station maintenance EVAs and were used in this test. Donning them is a common Shuttle task. In some instances, the MWS with tool caddies attached impeded crew view. Some crew members used the MWS retractable tether to hold the power tool, while others used it to brace themselves at the worksite and tethered the tool off to structure. One crew member suggested a holster on the EMU thigh to stow the power tool when not in use.

Crew members made several suggestions regarding tethering which could simplify the overhead tasks. Two tether points should be provided on every ORU or other item that must be handled, translated, or temporarily stowed. This includes all equipment that is transferred on the clothesline. Almost every test subject commented that tether protocol is extremely time-consuming and that procedures which reduce the number of tether operations.

CETA and Clothesline Device

Operation of the CETA device was found to be a generally efficient portion of the overhead tasks simulated. One-g effects on tools during CETA movement helped some test subjects and hindered others, according to crew comments. Since crew members could not release or restow objects on the CETA platform from the CETA PFR's, handrails were needed to react forces. Nevertheless, lack of handrails did not preclude completion of procedures nor affect the timelines.

The clothesline device used with the CETA cart received mixed comments from the crew members, most of whom felt that some ingenuity could produce a superior design. The inefficiency of the clothesline device prompted some test subjects to comment that it would be faster to carry each object one by one to and from a worksite located as close as the test pallet. A bi-stem extender, which was used on Skylab, was recommended in place of the clothesline for short distance translations like that simulated. Crew members felt that this was a better device than the clothesline for the overhead tasks of equipment transfer from the CETA to a pallet.

Transferring objects on the clothesline was time consuming. The clothesline tangled, and required two hands to use and two people to operate it. It also failed to fully control the movement of an object in transit. Placing the tether points near an object's c.g. was suggested by one test subject to ameliorate this last condition.

Objects were transferred on the clothesline one at a time as they were stowed. Crew members felt that stowing and transferring the entire PWP as a unit would save time if there were sufficient room to prevent the PWP from snagging on structure along the way. One evaluator stated emphatically that the EVA crew needs a linear path from the CETA to each worksite with sufficient clearances to transfer the ORUs and other required equipment. If this cannot be provided in a single bay, it should be provided by leaving truss facets in the adjacent bay empty.

The clothesline was sized with slack in the line for this test since crew members from a previous developmental WETF test preferred a slack rather than a taut line. One test subject in this exercise felt strongly that the line should be taut and that slack only added to the possibility of line tangling and thus extra overhead. The other crew members felt that a small amount of slack, up to the amount simulated, was helpful. The utility of the slack was mostly realized in the ability to directly attach items on the CETA to the clothesline and thus avoid wrist tether operations to transfer objects between the two. A clothesline modification that might satisfy both opinions on slack is retractable tether lines on the clothesline hooks. Thus, the clothesline could be taut, and the hooks could be attached to items on the CETA directly.

Pallet Operations

In general, crew members did not find the number of handrails to be adequate nor their placement optimum. Optimum placement was noted to be a matter of individual preference and differed between the pairs of crew who participated in the test. Ample handrails were suggested to reduce overhead for all EVA tasks near the worksite, including PFR and stanchion installation.

Installation of the stanchion was particularly time-consuming in every test run. The correct angular positioning of the stanchion was found to be critical. Incorrect positioning could place the ORU in the crew member's way or out of reach when temporarily stowed on the stanchion. To simplify stanchion installation, one crew member suggested a soft capture device on the probe. It should be noted that crew members in every test eventually worked as a pair to install the stanchion.

Crew members questioned the necessity of the stanchion. Tethering the ORU off to a tether point at the worksite was recommended if the stanchion's only purpose in a maintenance action is ORU temporary stowage. However, the stanchion would be necessary if required to hold lights or if ORU handrails are incorporated in the ORU removal and replacement tool and not available as PFR ingress aids. An alternative suggestion made during the tests was a bayonet clip or similar device located on the front of all ORUs so that ORUs or tools could be temporarily stowed on adjacent ORUs.

ORU Removal and Replacement

Test subjects gave generally favorable comments when queried about the candidate "box-type" ORU. Although it was not too large to move in or out of its installation position, one evaluator suggested using the HST socket adaptor to gain a little extra distance from the pallet.

In spite of some difficulties encountered with the hard dock feature mockup, crew members liked the tool. Nevertheless, they felt that hard docking the tool to the ORU was unnecessary unless the tool was indeed used as the ORU handing and tethering aid.

Crew members liked the ORU soft dock concept even though there were some mockup specific problems were encountered. They suggested that the ORU incorporate a positive soft dock which cannot become dislodged unintentionally. Test subjects liked the placement of the attachment bolts on either side of the box but felt that visual indicators should be provided to tell when the bolts are engaged and when they are released. Placing the tether points near the center of the ORU handrails rather than near the top of the ORU as they were in the test was also recommended.

Conclusions and Recommendations

The EVA Overhead Task Time Test was successful in that it accomplished all objectives set forth in the test plan. In addition, this test identified several flight crew recommendations which could be used to reduce EVA overhead and improve the overall EVA maintenance scenarios currently proposed for SSF.

The following is a summary of some of the specific recommendations made and shared by several crew members:

- Tether protocol is time-consuming and should be made as efficient as possible in the EVAs support equipment operation.
- Two tether points should be provided on every ORU or other item which must be handled, translated, or temporarily stowed. This includes all equipment which is transferred on the clothesline. The tether points should be close the the object's c.g.
- A bi-stem extender should be considered as a more efficient alternative to the clothesline.
- Areas to be maintained by EVA should be as close to the CETA as possible with a direct, unobstructed, and open pathway between the CETA and the worksite through which equipment can be transferred.
- Worksites should be equipped with adequate PFR ingress aids, lighting and ORU temporary stowage provisions, without the need for a stanchion in addition to the PFR, if possible.
- It is feasible for one crew member to accomplish all EVA overhead tasks simulated, although a certain timeline penalty will be incurred.

Appendix F

Attachment 2

TO: Fisher-Price External Maintenance Task Team

FROM: Fisher-Price EVA Video Analysis Team

SUBJECT: EVA Video Analysis for Space Station EVA overhead tasks

DATE: May 25, 1990

Summary of Video Analysis

Past EVA experience analagous to that on SSF was investigated to accurately quantify the amount of EVA time required for external maintenance on SSF. Many tasks performed during STS extravehicular activities are similar to those needed for SSF maintenance. Videotape coverage of these EVAs was transcribed into time-coded VHS format for analysis. A task time analysis of STS EVAs was completed, and the purpose of this report is to explain methods used to obtain data for the video time investigation.

This assessment was based on the ITA Generic EVA Task Timeline detailed EVA procedures. This paper includes how the task times were determined from viewing the EVA videotapes, formatting of spreadsheets for task time data entry, and ground rules and results on how data was entered.

Background

To date, engineering estimates have served as the primary means to determine the amount of EVA maintenance required for SSF. In order to consider the Space Shuttle EVA analogs to SSF maintenance, the following instructions served as the basis for the present work:

- Acquire VHS format EVA material from STS missions and WETF tests with the time code window;
- Review STS and WETF VHS tapes and get times of EVA tasks representative of SSF maintenance activities; and
- Enter task times from tapes into the Baseline EVA Overhead

  Timeline Database for use by the External Maintenance Task Team.

Methodology

Videotapes of STS missions 51-I, 61-B, STS-6, 41-B, 41-C, 41-G, 51-A, and 51-D were used as reference material and dubbed to VHS with a time-coded window. Viewing equipment and VHS tapes were made available with the assistance of the Photography and Television Technology Division at NASA/JSC.

The time of an EVA task begins when a previous procedure is completed, and the task time ends when the next step in the EVA procedure is started. For example, if an EVA crew member must soft-dock an ORU into a holding fixture, remove his or her wrist tether from the ORU, and reach for a power tool, the procedure time for untethering would be as follows:

- Procedure time starts when crew member finishes soft docking ORU and and reaches for his or her wrist tether; and
- Task time stops after wrist tether is released, restowed on wrist, and crew member first reaches for power tool (which is the next procedural task).

These methods for determining the times to complete STS and WETF EVA tasks were followed as best as possible for all primitive tasks. In cases, the EVA crew members experienced difficulties which extended the times of tasks. If these difficulties could be common to space station EVA maintenance, they were noted, and the EVA task time was included in the database. All occurrences of EVA tasks were considered valid if they could be observed from beginning to completion with no noted hardware failures. Task times acquired from videotape include long and short times; these large deviations in task times are equally applicable to SSF EVA and are due to snagged tethers, fatigue, body orientation, etc.

Spreadsheet Format

To perform the analysis, five linked EXCEL spreadsheets were created. The first four "pedigree" spreadsheets contained rows in which the detailed EVA overhead maintenance procedures were entered. The term, "pedigree," refers to the location and duration of a given EVA maintenance task on the WETF or STS mission videotapes. The columns in each spreadsheet included the mission number, reference tape numbers, GMT start/stop time, calculated task time, SMPTE (Society of Motion Picture and Television Engineers) time, and a comment field. The fifth spreadsheet averaged the task times from all four "pedigree" spreadsheets. For the WETF test data for SSF EVA maintenance, only three pedigree spreadsheets were used, and an average task time spreadsheet was also formed for the WETF video data.

Spreadsheet Task Data Entry

Many possible Shuttle tasks that are similar to SSF tasks were identified on each mission. Often, the complete task from start to stop was not available on the camera views, or the view angle was inappropriate; therefore, it was necessary to discard tasks in many instances. A statistically representative set of tasks was entered into each pedigree spreadsheet when an entire task was found with a good camera view. The first occurrence of an STS EVA task was entered into the first pedigree of the spreadsheet, and further occurrences of similar procedures were entered into successive pedigrees (e.g., two, three). For the WETF test data, tasks from the first, second, and third WETF test series were entered into the first, second, and third pedigrees, respectively.

Statistically representative sets of EVA procedures included pedigrees with tasks in which crew members had difficulty (e.g., tether tangling) in completing procedures and instances in which crew members accomplished tasks easily. If an EVA procedure applicable to SSF maintenance was inordinately long or difficult for an EVA crew member, the task was not placed into the Baseline EVA Overhead Timeline but it was included and documented in the comment field. For the WETF tests, a procedure time was placed into the database for the EVA crew member who had the least difficulty with the task. This was done so as not to bias the high data times due to immature hardware designs, imprecise mockups, and crew's having not been thoroughly trained on procedures.

To randomize the data sampling, as many different missions as possible were used as sources for a given task. The most missions used for a given maintenance task were nine, for "tether to object.".

Discussion of Results

In some instances, identical procedures have been performed on-orbit (e.g. ingressing a PFR). In other cases, a generic piece of equipment was used for a specific task. For example, if EV1 tethered to a large satellite handling bar while passing the bar to EV2, this task would be analogous to EV1 tethering to a Work Station Stanchion while passing it to EV2. Analogies were noted in the comment field.

In the WETF tests, most tasks were done with reasonable fidelity for determination of EVA maintenance times. Some procedures were done out of sequence, but only individual subtask times were acquired. Because the time available for procedures did not allow stowage of tools to be accomplished by the crew members, the WETF tests did not show a result for tool stowage. The airlock egress time and tool unstowage was accomplished only once for each WETF test without any practice; therefore, these times may not be as accurate. They did not, however, affect the final EMTT EVA overhead predictions since ample flight data was acquired for airlock ingress/egress.

Pedigrees one through four contain Shuttle tasks that were analogous to SSF tasks involving the PFR, MWS, airlock, and tool box. SSF-specific data like CETA, ORUs, and clothesline operations are not represented because no similar tasks found during Shuttle EVA operations.

Fisher-Price EVA video analysis team

Mike Hess
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Appendix F

Attachment 3

	A	C	D	E	F	G	H	I	J	L	M	N	O	P	Q	R	W
1	TASKS	PEDIGREE					GMT Start Time				GMT Stop Time				Task Time	SMPTE	AVERAGES
2		Mission #	REF Tape 1	REF Tape 2	REF Tape 3	REF Tape 4	HRS	MINS	SECS		HRS	MINS	SECS		HRS:MINS:SECS	HRS:MINS:SECS	
3																	0:00:29
4	TETHER TO OBJECT																
5																	
6	Tether to Mini Workstations	41C	110191	110335	111447	112158	3	2	13		3	2	19		0:00:06	SMPTE only	
7	Tether to Mini Workstations	41C	112153	112151	112161	112156	8	10	2		8	10	10		0:00:08	SMPTE only	
8	Tether to PWP foot restraint	41C	110191	110335	111447	112158	3	5	40		3	6	1		0:00:21	SMPTE only	
9	Tether to PWP foot restraint	41C	112153	112151	112161	112156	8	9	22		8	9	42		0:00:20	SMPTE only	
10	Tether to tool (EV1 and EV2)	STS6	111650	111634	111651		8	41	39		8	42	50		0:01:11	SMPTE only	
11	Tether to tool (EV1 and EV2)	STS-6	111650	111634	111651		8	42	55		8	43	53		0:00:58	SMPTE only	
12	Tether to tool (EV1 and EV2)	STS6	111650	111634	111651		8	44	6		8	45	3		0:00:57	SMPTE only	
13	Tether to tool (EV1 and EV2)	STS6	111650	111634	111651		8	44	6		8	45	3		0:00:57	SMPTE only	
14	Tether to PWP foot restraint	511	112665	112206			13	0	13		13	0	33		0:00:20		
15	EV2 secure left waist tether to airlock	WETF 1	WO01031	1 of 3	5/21/90	float 1	18	5	26		18	5	37		0:00:11		
16	EV1 secure right waist tether to EV2s right waist teth	WETF 1	WO01031	1 of 3	5/21/90	float 1	18	5	39		18	5	49		0:00:10		
17	EV1 secure L w-tether to CETA safety tether D-ring #	WETF 1	33918	1 of 3	5/21/90	29-4	18	6	18		18	6	37		0:00:19		
18	EV1 unhook EV2's R waist tether & attach to D-ring #2	WETF 1	33918	1 of 3	5/21/90	29-4	18	6	39		18	6	56		0:00:17		
19	EV1 tether to PWP foot restraint	WETF 1	WO01031	2 of 3	5/21/90	EV2	19	48	50		19	50	28		0:01:38		
20	Tether to clothes line end	WETF 1	33921	2 of 3	5/21/90	29-4	19	50	28		19	51	31		0:01:03		
21	EV2 tether to PWP stanchion	WETF 1	WO01031	2 of 3	5/21/90	EV1	19	51	27		19	51	57		0:00:30		
22	EV1 tether to stanchion	WETF 1	WO01031	2 of 3	5/21/90	EV2	20	7	38		20	8	12		0:00:34		
23	EV2 tether to ORU	WETF 1	WO01031	2 of 3	5/21/90	EV2	20	15	21		20	15	36		0:00:15		
24	EV1 tether to ORU	WETF 1	WO01031	2 of 3	5/21/90	EV2	20	17	57		20	18	20		0:00:23		
25	Tether to stanchion	WETF 1	WO01031	2 of 3	5/21/90	EV2	20	37	7		20	37	48		0:00:41		
26	Tether to stanchion	WETF 1	WO01031	2 of 3	5/21/90	EV1	20	42	47		20	43	13		0:00:26		
27	EV1 tether to PFR	WETF 1	WO01031	2 of 3	5/21/90	EV2	20	42	58		20	43	12		0:00:14		
28	Tether to failed ORU	WETF 1	WO01031	2 of 3	5/21/90	EV2	20	28	37		20	28	51		0:00:14		
29	EV2 secure left waist tether to airlock	WETF 2	WO01031	1 of 2	5/22/90	float 1	13	19	16		13	19	22		0:00:06		
30	EV1 secure right waist tether to EV2s right waist teth	WETF 2	WO01031	1 of 2	5/22/90	float 2	13	19	55		13	20	9		0:00:14		
31	EV1 secure L w-tether to CETA safety tether D-ring #	WETF 2	WO01031	1 of 2	5/22/90	float 2	13	20	46		13	21	10		0:00:24		
32	EV1 unhook EV2's R waist tether & attach to D-ring #2	WETF 2	WO01031	1 of 2	5/22/90	float 2	13	21	10		13	22	5		0:00:55		
33	Tether to Mini Workstations	WETF 2	WO01031	1 of 2	5/22/90	float 1	13	25	17		13	25	27		0:00:10		
34	Tether to tool (EV1 and EV2)	WETF 2	WO01031	1 of 2	5/22/90	float 1	13	25	49		13	25	54		0:00:05		
35	Tether to tool	WETF 2	WO01031	1 of 2	5/22/90	float 1	13	26	4		13	26	11		0:00:07		
36	Tether to tool	WETF 2	WO01031	1 of 2	5/22/90	float 2	13	32	6		13	32	54		0:00:48		
37	Tether to clothes line end	WETF 2	WO01031	1 of 2	5/22/90	float 1	14	42	40		14	43	3		0:00:23		
38	EV2 tether to PWP stanchion	WETF 2	33940	2 of 2	5/22/90	29-4	15	40	3		15	40	19		0:00:16		
39	EV1 tether to stanchion	WETF 2	33950	2 of 2	5/22/90	29-2	15	42	22		15	42	38		0:00:16		
40	EV1 tether to ORU	WETF 2	WO01031	2 of 2	5/22/90	float 1	15	50	22		15	50	55		0:00:33		
41	EV2 tether to ORU	WETF 2	WO01031	2 of 2	5/22/90	float 2	15	59	6		15	59	28		0:00:22		
42	Tether to stanchion	WETF 2	33949	2 of 2	5/22/90	29-2	16	2	54		16	3	18		0:00:24		
43	Tether to failed ORU	WETF 2	33949	2 of 2	5/22/90	29-2	15	58	3		15	58	17		0:00:14		
44	Tether to stanchion	WETF 2	33942	2 of 2	5/22/90	29-4	16	22	19		16	22	51		0:00:32		
45	EV1 tether to PWP foot restraint	WETF 3	WO01031	5/22/90	1 of 3	float 2	21	36	0		21	36	14		0:00:14		
46	Tether to clothes line end	WETF 3	33946	5/22/90	1 of 3	29-4	21	31	30		21	32	12		0:00:42		
47	EV1 tether to stanchion	WETF 3	WO01031	5/22/90	1 of 3	float 1	21	48	18		21	48	48		0:00:30		
48	EV1 tether to ORU	WETF 3	WO01031	5/22/90	1 of 3	float 1	21	59	14		22	0	50		0:01:36		
49																	0:00:21
50	RELEASE TETHER																
51																	
52	Release tether	41C	112162	112165	111015	112167	11	39	53		11	40	8		0:00:15	SMPTE only	
53	Release tether	41C	110191	110335	111447	112158	3	3	36		3	3	56		0:00:20	SMPTE only	
54	EV1 release tether	511	112665	112206			13	0	4		13	0	8		0:00:04		
55	EV1 release tether	51D	112708	112735			15	13	31		15	13	56		0:00:25	SMPTE time	

	A	C	D	E	F	G	H	I	J	L	M	N	O	P	Q	R	W
56	Release tether	51D	112708	112735			15	13	31		15	13	56		0:00:25	SMPTE time	
57	EV2 unhook left waist tether	WETF 1	WO01031	1 of 3	5/21/90	float 2	18	6	55		18	7	49		0:00:54		
58	Release clothesline tether & attach to pallet	WETF 1	WO01031	2 of 3	5/21/90	EV2	20	1	23		20	2	35		0:01:12		
59	Release tether	WETF 1	WO01031	2 of 3	5/21/90	EV2	20	41	20		20	41	26		0:00:06		
60	Release clothesline & attach to tether	WETF 1	WO01031	2 of 3	5/21/90	EV2	20	46	43		20	47	0		0:00:17		
61	Release ORU tether	WETF 1	WO01031	2 of 3	5/21/90	EV2	20	28	9		20	28	18		0:00:09		
62	Release tether	WETF 1	WO01031	2 of 3	5/21/90	EV2	20	12	16		20	12	41		0:00:25		
63	EV2 unhook left waist tether	WETF 2	33937	1 of 2	5/22/90	29-4	13	20	45		13	20	55		0:00:10		
64	Release tether	WETF 2	WO01031	1 of 2	5/22/90	float 1	13	25	42		13	25	49		0:00:07		
65	EV1 release tether	WETF 2	WO01031	1 of 2	5/22/90	float 1	13	25	7		13	25	17		0:00:10		
66	EV1 release tether	WETF 2	33936	1 of 2	5/22/90	29-2	13	26	14		13	26	30		0:00:16		
67	Release clothesline tether & attach to pallet	WETF 2	WO01031	1 of 2	5/22/90	float 1	14	47	41		14	49	0		0:01:19		
68	Release tether	WETF 2	WO01031	2 of 2	5/22/90	float 1	15	41	16		15	41	38		0:00:22		
69	Release tether	WETF 2	33949	2 of 2	5/22/90	29-2	15	59	34		15	59	40		0:00:06		
70	Remove tether	WETF 2	WO01031	2 of 2	5/22/90	float 2	16	23	36		16	23	46		0:00:10		
71	Release clothesline tether	WETF 2	33949	2 of 2	5/22/90	29-2	16	22	49		16	23	2		0:00:13		
72	Remove tether	WETF 2	WO01031	2 of 2	5/22/90	float 2	16	19	17		16	19	27		0:00:10		
73	Release tether	WETF 2	WO01031	2 of 2	5/22/90	float 2	15	43	44		15	43	48		0:00:04		
74	Release tether	WETF 2	WO01031	2 of 2	5/22/90	float 1	16	21	12		16	21	21		0:00:09		
75	Release clothesline tether & attach to pallet	WETF 3	WO01031	5/22/90	1 of 3	float 1	21	33	48		21	33	55		0:00:07		
76	Release tether to PFR	WETF 3	WO01031	5/22/90	1 of 3	float 1	21	44	35		21	45	24		0:00:49		
77	Release tether	WETF 3	WO01031	5/22/90	1 of 3	float 1	21	52	45		21	53	19		0:00:34		
78																	
79	INGRESS PFR																0:00:28
80																	
81	Ingress PFR	61B	113977	113996			22	47	22		22	47	33		0:00:11		
82	Ingress PFR	61B	113896	113902	113905		1	13	20		1	13	37		0:00:17		
83	Ingress PFR	51I	112665	112206			12	36	0		12	36	14		0:00:14		
84	Ingress Foot Restraint	SKY3					23	12	41		23	12	51		0:00:10		
85	Ingress PFR	WETF 1	WO01031	2 of 3	5/21/90	EV2	20	20	55		20	21	12		0:00:17		
86	EV1 and EV2 ingress PFRs	WETF 1	WO01031	2 of 3	5/21/90	EV2	20	58	1		20	58	41		0:00:40		
87	EV1 and EV2 ingress CETA PFRs	WETF 2	33939	1 of 2	5/22/90	29-4	14	35	30		14	36	4		0:00:34		
88	Ingress PFR	WETF 2	WO01031	2 of 2	5/22/90	float 1	15	53	32		15	53	37		0:00:05		
89	EV1 and EV2 ingress PFRs	WETF 2	WO01031	2 of 2	5/22/90	float 1	16	24	18		16	26	14		0:01:56		
90	Ingress PFR	WETF 3	WO01031	5/22/90	1 of 3	float 1	22	7	4		22	7	16		0:00:12		
91																	
92	EGRESS PFR																0:00:09
93																	
94	EV1 egress PFR	61B	113977	113996			0	7	55		0	8	9		0:00:14		
95	Egress Foot Restraint	SKY3					23	26	46		23	26	56		0:00:10		
96	Egress PFR	WETF 1	33921	2 of 3	5/21/90	EV2	19	47	17		19	47	29		0:00:12		
97	EV1 egress PWP	WETF 1	WO01031	2 of 3	5/21/90	EV2	20	33	35		20	33	40		0:00:05		
98	Egress PFR	WETF 2	WO01031	1 of 2	5/22/90	float 1	14	36	46		14	36	49		0:00:03		
99	EV1 egress PWP	WETF 2	WO01031	2 of 2	5/22/90	float 1	15	58	38		15	58	44		0:00:06		
100	Egress PFR	WETF 3	WO01031	5/22/90	1 of 3	float 1	21	30	50		21	31	6		0:00:16		
101																	
102	INSTALL OBJECT																0:33:41
103																	
104	Install PFR	STS6	111602	111634			13	42	19		13	45	19		0:03:00	SMPTE only	
105	Install PWP PFR in socket	WETF 2	33940	1 of 2	5/22/90	29-4	14	48	2		14	51	31		0:03:29		
106	Install PWP PFR in socket	WETF 3	WO01031	5/22/90	1 of 3	float 1	21	40	0		21	44	35		0:04:35		
107																	
108	ATTACH OBJECT																0:00:45
109																	
110	Attach ORU to clothesline hook	41C	112153	112151	112151	112156	8	10	22		9	10	50		0:00:28	SMPTE only	

	A	C	D	E	F	G	H	I	J	L	M	N	O	P	O	R	W
111	Attach ORU to clothesline hook	WETF 1	WO01031	2 of 3	5/21/90	EV2	20	34	48		20	35	45		0:00:57		
112	Attach stanchion to clothesline hook	WETF 1	33927	2 of 3	5/21/90	29-4	20	40	38		20	41	20		0:00:42		
113	Attach stanchion to clothesline hook	WETF 2	WO01031	2 of 2	5/22/90	float 1	15	40	19		15	41	16		0:00:57		
114	Attach ORU to clothesline hook	WETF 2	33940	2 of 2	5/22/90	29-4	15	44	9		15	46	24		0:02:15		
115	Attach ORU to clothesline hook	WETF 2	WO01031	2 of 2	5/22/90	float 2	15	59	4		15	59	30		0:00:26		
116	Attach stanchion to clothesline hook	WETF 2	WO01031	2 of 2	5/22/90	float 1	16	21	6		16	21	12		0:00:06		
117	Attach ORU to clothesline hook	WETF 3	WO01031	5/22/90	1 of 3	float 2	21	57	3		21	57	11		0:00:08		
118																	
119	RELEASE OBJECT																0:00:28
120																	
121		WETF 1	WO01031	2 of 3	5/21/90	EV2	20	8	12		20	8	36		0:00:24		
122	Release ORU from clothesline	WETF 1	WO01031	2 of 3	5/21/90	EV2	20	18	20		20	18	42		0:00:22		
123	Release ORU from clothesline	WETF 2	WO01031	2 of 2	5/22/90	float 2	15	50	51		15	51	48		0:00:57		
124	Release ORU from clothesline	WETF 2	33942	2 of 2	5/22/90	29-4	16	3	53		16	4	19		0:00:26		
125	Remove stanchion from clothesline hook	WETF 2	WO01031	2 of 2	5/22/90	float 2	16	22	61		16	23	2		0:00:11		
126																	
127	TRANSFER OBJECT																0:01:50
128																	
129	Tranfer ORU to worksite	41C	112153	112151	112161	112156	8	12	53		8	15	38		0:02:45	SMTE only	
130	Transfer stanchion to worksite	WETF 1	WO01031	2 of 3	5/21/90	EV1	20	2	23		20	4	1		0:01:38		
131	Tranfer ORU to worksite	WETF 1	WO01031	2 of 3	5/21/90	EV1	20	16	25		20	17	57		0:01:32		
132	Transfer ORU back to CETA	WETF 1	33933	2 of 3	5/21/90	EV2	20	35	45		20	36	56		0:01:11		
133	EV2 transfer stanchion to CETA	WETF 1	WO01031	2 of 3	5/21/90	EV1	20	42	18		20	42	47		0:00:29		
134	Transfer stanchion to worksite	WETF 2	33940	2 of 2	5/22/90	29-4	15	41	38		15	42	22		0:00:44		
135	Tranfer ORU to worksite	WETF 2	WO01031	2 of 2	5/22/90	float 2	15	46	40		15	50	51		0:04:11		
136	Transfer ORU back to CETA	WETF 2	WO01031	2 of 2	5/22/90	float 2	15	59	28		16	4	25		0:04:57		
137	EV2 transfer stanchion to CETA	WETF 2	33949	2 of 2	5/22/90	29-4	16	21	21		16	22	19		0:00:58		
138	Transfer stanchion to worksite	WETF 3	33947	5/22/90	1 of 3	29-2	21	47	24		21	48	16		0:00:52		
139	Tranfer ORU to worksite	WETF 3	WO01031	5/22/90	1 of 3	float 2	21	57	30		21	58	24		0:00:54		
140																	
141	EGRESS AIRLOCK																0:08:47
142																	
143	Open EVA hatch	61B	113485				21	48	45		21	59	35		0:10:50	15.39.18	
144	Open EVA hatch	STS-6	111650	111634	111651		9	50	52		10	5	3		0:14:11	SMPTE only	
145	Open EVA hatch	41B	110714	111674	111951	111364	21	14	9		21	17	55		0:03:46	SMPTE only	
146	Open EVA hatch	51I	113676	112748			12	14	40		12	21	0		0:06:20		
147																	
148																	
149	OPEN TOOLBOX DOOR																0:01:02
150																	
151	Open toolbox door	41C	112153	112151	112161	112156	8	8	22		8	9	22		0:01:00	SMPTE only	
152	Open toolbox door	41B	111571	111622	111876	111645	18	59	13		19	0	17		0:01:04	SMPTE time	
153																	
154																	
155	INGRESS AIRLOCK																0:06:11
156																	
157	EV2 enter airlock	41B	110714	111674	111951	111364	16	36	0		16	40	0		0:04:00		
158	EV2 enter airlock	51D	112708	112735			15	22	0		15	28	14		0:06:14	SMPTE time	
159	EV2 enter airlock	41G	110934	110562			18	25	44		18	34	2		0:08:18	SMPTE time	
160																	
161																	
162	ATTACH MWS TO EMU																0:00:52
163																	
164	Attach MWS to EMU	41C	110191	110335	111447	112158	3	2	19		3	2	51		0:00:32	SMPTE only	
165	Attach MWS to EMU	41C	112162	112165	111015	112167	11	38	40		11	39	53		0:01:13	SMPTE only	

	A	C	D	E	F	G	H	I	J	L	M	N	O	P	Q	R	W
166																	
167																	
168	CLOSE TOOLBOX DOOR																0:02:07
169																	
170	Close tool box	STS-6	111650	111634	111651		10	9	25		10	10	8		0:00:43	SMPTE only	
171	Close tool box	41B	110714	111674	111951	111364	16	25	10		16	28	40		0:03:30	SMPTE time	
172																	
173																	
174	REMOVE ORU CAPTIVE BOLTS																0:05:14
175																	
176	Remove ORU captive bolts	51A	110029	110480	110067	110110	9	29	57		9	35	11		0:05:14	SMPTE time	
177																	
178																	
179	TETHER TO PFR AND REMOVE FROM SOCKET																0:03:16
180																	
181	EV1 tether to PFR & remove from socket	STS6	111602	111634			11	31	50		11	35	6		0:03:16	SMPTE only	
182																	
183	INSTALL STANCHION																0:00:42
184																	
185	Install stanchion	51I	112665	112206			12	38	53		12	39	35		0:00:42		
186																	
187																	
188	REMOVE TOOL FROM MWS																0:00:26
189																	
190	Remove tool from MWS	STS-6	111559	111634	111643		13	26	0		13	26	13		0:00:13	SMPTE only	
191	Remove tool from MWS	WETF 1	WO01031	2 of 3	5/21/90	EV2	20	25	35		20	26	0		0:00:25		
192	Remove tool from MWS	WETF 2	WO01031	2 of 2	5/22/90	float 1	15	53	54		15	54	33		0:00:39		
193																	
194																	
195	RELEASE MWS FROM EMU																0:00:16
196																	
197	Release MWS from EMU	51D	112708	112735			15	12	14		15	12	39		0:00:25	SMPTE only	
198	Release MWS from EMU	STS-6	111602	111634			0	49	51		0	49	58		0:00:07	SMPTE only	
199																	
200																	
201	REPLACE MWS INTO TOOLBOX																0:01:15
202																	
203	Replace MWS in toolbox	51D	112708	112735			15	12	39		15	13	31		0:00:52	SMPTE time	
204	Replace MWS in toolbox	STS-6	111602	111634			0	49	58		0	51	35		0:01:37	SMPTE only	
205																	
206																	
207	EV1 PASS PWP PFR TO EV2																0:00:19
208																	
209	EV1 pass PWP PFR to EV2	51I	112665	112206			12	57	25		12	57	44		0:00:19		
210																	
211																	
212	CLOSE THERMAL COVER/EVA HATCH																0:01:03
213																	
214	Close EVA hatch	61B	113896	113902	113905		2	57	27		2	58	30		0:01:03		
215																	
216																	
217	GET TOOL																0:01:11
218																	
219	Tether to tool (EV1 and EV2)	STS6	111650	111634	111651		8	41	39		8	42	50		0:01:11	SMPTE only	
220	Release tool from tool box														0:00:00		

	A	C	D	E	F	G	H	I	J	L	M	N	O	P	Q	R	W
221	Attach tool to MWS	•													0:00:00		
222	Release tether	•													0:00:00		
223																	

Appendix F

Attachment 4

	A	B	C	D	E	F
	TASKS	ASSUMPTIONS	TASK TIME	SUMMARY TIME	PRIMITIVE	SOURCE
1						
2				0:09:45		
3	EGRESS AIRLOCK					
4						
5	EV2 secure left waist tether to airlock	2 crewmen req'd for EVA	0:00:29		0:00:29	F&W avg
6	EV1 secure right waist tether to EV2s right waist tether		0:00:29		0:00:29	F&W avg
7	Open EVA hatch		0:08:47		0:08:47	F avg
8	EV1 exit airlock		0:00:00		0:00:00	F avg
9	EV1 secure L w-tether to CETA safety tether D-ring #1	Safety tethers secured to CETA	0:00:00		0:00:00	F avg
10	EV1 unhook EV2's R waist tether & attach to D-ring #2	Reel cases routed to airlock	0:00:00		0:00:00	F avg
11	EV2 unhook left waist tether		0:00:00		0:00:00	F avg
12	EV2 exit airlock		0:00:00		0:00:00	F avg
13	Remove safety tethers from pouches	Reel cases stowed - soft carry pouch	0:00:00		0:00:00	F avg
14	Unlock safety tethers		0:00:00		0:00:00	F avg
15				0:09:39		
16	ACQUIRE TOOLS					
17						
18	Translate to toolbox (ESE&T stowage) on airlock	PFR not necessary or already there	0:01:00		0:01:00	eng. est
19	Ingress PFR		0:00:28		0:00:28	F & W avg
20	Open toolbox door	EV1 and EV2 work in parallel	0:01:02		0:01:02	F avg
21	Tether to Mini Workstations		0:00:29		0:00:29	F&W avg
22	Release Mini Workstation from tool box		0:00:10		0:00:10	engr. est
23	Attach MWS to EMU		0:00:52		0:00:52	F avg
24	Release tether		0:00:21		0:00:21	F&W avg
25	Tether to tool (EV1 and EV2)	Two tools necessary for one task	0:01:11		0:01:11	F avg
26	Release tool from tool box		0:00:00		0:00:00	F avg
27	Attach tool to MWS		0:00:00		0:00:00	F avg
28	Release tether		0:00:00		0:00:00	F avg
29	Tether to tool		0:01:11		0:01:11	F avg
30	Release tool from toolbox		0:00:00		0:00:00	F avg
31	Attach tool to MWS	Tool remains tethered	0:00:00		0:00:00	F avg
32	EV2 tether to clothesline		0:00:29		0:00:29	F&W avg
33	Release clothesline from toolbox		0:00:10		0:00:10	engr. est
34	Close tool box		0:02:07		0:02:07	F avg
35	Egress PFR		0:00:09		0:00:09	F & W avg
36				0:08:19		
37	ACQUIRE PORTABLE WORK PLATFORM					
38						
39	EV2 translate to CETA		0:01:00		0:01:00	engr. est
40	Tether clothesline to CETA		0:00:29		0:00:29	F&W avg
41	Release tether		0:00:21		0:00:21	F&W avg
42	EV1 translate to PWP stowage	Parallel action with EV2	0:00:00		0:01:00	engr. est
43	Ingress PFR	Parallel action with EV2	0:00:00		0:00:28	F & W avg
44	Open PWP container doors	Partially parallel with EV2	0:00:40		0:01:02	F avg
45	Tether to PWP foot restraint		0:00:29		0:00:29	F & W avg
46	Release PWP foot restraint from container		0:00:10		0:00:10	engr. est
47	EV1 pass PWP PFR to EV2		0:00:19		0:00:19	F data point
48	EV2 tether to PWP PFR		0:00:29		0:00:29	F & W avg
49	EV1 release tether		0:00:21		0:00:21	F & W avg
50	EV2 attach PWP foot restraint to CETA ORU carrier		0:03:41		0:03:41	F & W avg
51	EV2 release PWP tether		0:00:00		00:00:00	F & W avg
52	EV1 tether to PWP stanchion	Parallel action with EV2	0:00:00		0:00:29	F & W avg
53	Release PWP stanchion from stowage container	Parallel action with EV2	0:00:00		0:00:10	engr. est
54	Close PWP stowage door	Parallel action with EV2	0:00:00		0:01:00	engr. est
55	Egress PFR	Parallel action with EV2	0:00:00		0:00:09	F & W avg

	A	B	C	D	E	F
56	Translate to CETA	Parallel action with EV2	0:00:00		0:01:00	engr. est
57	Attach stanchion to CETA	Parallel action with EV2	0:00:00		0:00:42	F data point
58	Release stanchion tether	Partially parallel action	0:00:20		0:00:21	F & W avg
59						
60	TRANSLATE TO MAIN CETA RAIL			0:04:48		
61						
62	EV1 and EV2 ingress CETA PFRs		0:00:28		0:00:28	F & W avg
63	Release CETA brake		0:00:10		0:00:10	Eng. est
64	Translate along CETA rail past spur switching mechanism		0:00:10		0:00:10	Engr. est
65	Set CETA brake		0:00:10		0:00:10	Engr. est
66	Rotate CETA for translation in opposite direction		0:02:00		0:02:00	Engr. est
67	Release rail spur deadbolt latch		0:00:15		0:00:15	Engr. est
68	Move spur/CETA to main rail		0:00:30		0:00:30	Engr. est
69	Release CETA brake		0:00:15		0:00:15	Engr. est
70	Engage rail spur deadbolt latch		0:00:10		0:00:10	Engr. est
71	Translate to unpressurized logistics carrier		0:00:30		0:00:30	Engr. est
72	Set CETA brake		0:00:10		0:00:10	Engr. est
73						
74	ACQUIRE ORU			0:29:52		
75						
76	EV1 egress PFR		0:00:09		0:00:09	F & W avg
77	Tether to PFR		0:03:16		0:03:16	F & W avg
78	Remove PFR from socket		0:00:00		0:00:00	F & W avg
79	Tether to clothesline end		0:00:29		0:00:29	F & W avg
80	Translate to ORU stowage slot	Translation along struts is	0:01:00		0:01:00	engr. est
81	Remove clothesline, attach to ULC & adjust	Attachment point available	0:01:00		0:01:00	engr. est
82	Install PFR on ULC	permissible	0:03:41		0:03:41	F & W avg
83	Remove tether		0:00:00		0:00:00	F & W avg
84	Ingress PFR		0:00:28		0:00:28	F & W avg
85	Open ULC	Two latches	0:01:02		0:01:02	F avg
86	Tether to ORU		0:00:29		0:00:29	F & W avg
87	Remove tool from MWS	Bayonet clip mount, already tethered	0:00:26		0:00:26	F & W avg
88	Remove ORU captive bolts	Four bolts	0:05:14		0:05:14	F data point
89	Attach tool to MWS		0:00:15		0:00:15	Engr. est
90	Remove ORU from stowage slot	Connectors are blind mated/demated	0:01:00		0:01:00	engr. est
91	Attach ORU to clothesline hook		0:00:28		0:00:28	F & W avg
92	Remove tether		0:00:21		0:00:21	F & W avg
93	EV2 transfer ORU to CETA		0:01:50		0:01:50	W avg
94	Tether to ORU		0:00:29		0:00:29	F & W avg
95	Remove ORU from Clothesline		0:00:28		0:00:28	W avg
96	Attach ORU to CETA ORU carrier		0:01:30		0:01:30	Engr. est
97	Release tether to ORU		0:00:21		0:00:21	F & W avg
98	EV1 close ULC	Done in parallel with EV2 tasks	0:00:00		0:01:02	engr. est
99	Egress PFR	Done in parallel with EV2 tasks	0:00:00		0:00:09	F & W avg
100	Tether to PFR	Done in parallel with EV2 tasks	0:00:00		0:03:16	F & W avg
101	Remove PFR from socket	Done in parallel with EV2 tasks	0:00:00		0:00:00	F & W avg
102	Release clothesline & tether to clothesline end	Partially parallel with EV2 tasks	0:00:18		0:00:29	F&W avg
103	Translate to CETA		0:01:00		0:01:00	engr. est
104	Release clothesline & replace on CETA		0:00:29		0:00:29	F&W avg
105	Replace PFR on CETA		0:03:41		0:03:41	F & W avg
106	Release tether		0:00:00		0:00:00	F & W avg
107	Ingress PFR		0:00:28		0:00:28	F & W avg
108						
109	TRANSLATE TO WORKSITE			0:01:20		
110						

	A	B	C	D	E	F
111	Release CETA brake		0:00:10		0:00:10	Engr. est
112	Translate to port maintenance worksite	Inboard of alpha joint	0:01:00		0:01:00	Engr. est
113	Set CETA brake		0:00:10		0:00:10	Engr. est
114						
115	**WORKSITE SETUP**			**0:16:29**		
116						
117	Egress PFR		0:00:09		0:00:09	F & W avg
118	EV1 tether to PWP foot restraint	Crew can carry foot restraint &	0:03:16		0:03:16	F & W avg
119	Release foot restraint from CETA	clothesline at same time	0:00:00		0:00:00	F & W avg
120	Tether to clothes line end		0:00:29		0:00:29	F & W avg
121	Translate along truss to worksite	Translation along truss is allowed	0:01:00		0:01:00	Engr. est
122	Release clothesline tether , attach to pallet & adjust	Clear path from worksite to CETA	0:01:00		0:01:00	engr. est
123	Install PWP PFR in socket	Socket available at worksite	0:03:41		0:03:41	F & W avg
124	Release tether to PFR		0:00:00		0:00:00	F & W avg
125	EV2 tether to PWP stanchion	Done in parallel with EV1 tasks	0:00:00		0:00:29	F & W avg
126	Release stanchion from CETA	Done in parallel with EV1 tasks	0:00:00		0:00:30	Engr. est
127	Attach stanchion to clothesline hook	Done in parallel with EV1 tasks	0:00:00		0:00:28	F & W avg
128	Release tether	Done in parallel with EV1 tasks	0:00:00		0:00:21	F & W avg
129	Transfer stanchion to worksite	Done in parallel with EV1 tasks	0:00:00		0:01:50	W avg
130	EV1 tether to stanchion		0:00:29		0:00:29	F & W avg
131	Release stanchion from clothesline		0:00:28		0:00:28	W avg
132	Install stanchion		0:00:42		0:00:42	F data point
133	Release tether to stanchion		0:00:21		0:00:21	F & W avg
134	EV2 tether to ORU	Done in parallel with EV1 tasks	0:00:00		0:00:29	F & W avg
135	Release ORU from CETA	Done in parallel with EV1 tasks	0:00:00		0:00:30	Engr. est
136	Attach ORU to clothesline hook	Done in parallel with EV1 tasks	0:00:00		0:00:28	F & W avg
137	Release tether	Done in parallel with EV1 tasks	0:00:00		0:00:21	F & W avg
138	Tranfer ORU to worksite	Partially parallel with EV1 tasks	0:01:38		0:01:50	W avg
139	EV1 tether to ORU		0:00:29		0:00:29	F & W avg
140	Release ORU from clothesline		0:00:28		0:00:28	W avg
141	Attach ORU to PWP		0:01:30		0:01:30	Engr. est
142	Release tether		0:00:21		0:00:21	F & W avg
143	Ingress PFR		0:00:28		0:00:28	F & W avg
144	EV2 translate along truss to worksite	Done in parallel with EV1 tasks	0:00:00		0:01:00	Engr. est
145	Release clothesline & attach to tether	Done in parallel with EV1 tasks	0:00:00		0:00:29	F&W avg
146	Translate to CETA	Done in parallel with EV1 tasks	0:00:00		0:01:00	engr. est
147	Release clothesline & replace on CETA	Done in parallel with EV1 tasks	0:00:00		0:00:29	F & W avg
148						
149						
150	****EV1 PERFORM MAINTENANCE TASK****		1:00:00	1:00:00	1:00:00	
151						
152		EV2 SETS UP ORU AT 2nd WORKSITE				
153	**TRANSLATE TO ORU CARRIER**					
154				0:00:00		
155	EV2 rotate CETA for translation in opposite direction	Done in parallel with EV1 tasks	0:00:00		0:02:00	Engr. est
156	Ingress CETA PFR	Done in parallel with EV1 tasks	0:00:00		0:00:28	F & W avg
157	Translate to ULC	Done in parallel with EV1 tasks	0:00:00		0:01:00	Engr. est
158						
159	**ACQUIRE ORU**			**0:00:00**		
160						
161	Egress PFR	Done in parallel with EV1 tasks	0:00:00		0:00:09	F & W avg
162	Tether to PFR	Done in parallel with EV1 tasks	0:00:00		0:03:16	F & W avg
163	Remove PFR from socket	Done in parallel with EV1 tasks	0:00:00		0:00:00	F & W avg
164	Tether to clothesline and	Done in parallel with EV1 tasks	0:00:00		0:00:29	F & W avg
165	Translate to ORU stowage slot	Done in parallel with EV1 tasks	0:00:00		0:01:00	Engr. est

	A	B	C	D	E	F
166	Remove Clothesline, attach to ULC & adjust	Done in parallel with EV1 tasks	0:00:00		0:01:00	engr. est
167	Install PFR on ULC	Done in parallel with EV1 tasks	0:00:00		0:03:41	F & W avg
168	Remove tether	Done in parallel with EV1 tasks	0:00:00		0:00:00	F & W avg
169	Open ULC	Done in parallel with EV1 tasks	0:00:00		0:01:02	F avg
170	Ingress PFR	Done in parallel with EV1 tasks	0:00:00		0:00:28	F & W avg
171	Tether to ORU	Done in parallel with EV1 tasks	0:00:00		0:00:29	F & W avg
172	Remove tool from MWS	Done in parallel with EV1 tasks	0:00:00		0:00:26	F & W avg
173	Remove ORU captive bolts	Done in parallel with EV1 tasks	0:00:00		0:05:14	F data point
174	Attach tool to MWS	Done in parallel with EV1 tasks	0:00:00		0:00:15	Engr. est
175	Remove ORU from stowage slot	Done in parallel with EV1 tasks	0:00:00		0:01:00	Engr. est
176	Attach ORU to clothesline hook	Done in parallel with EV1 tasks	0:00:00		0:00:28	F & W avg
177	Remove tether	Done in parallel with EV1 tasks	0:00:00		0:00:21	F & W avg
178	Transfer ORU to CETA	Done in parallel with EV1 tasks	0:00:00		0:01:50	W avg
179	Egress PFR	Done in parallel with EV1 tasks	0:00:00		0:00:09	F & W avg
180	Translate to CETA	Done in parallel with EV1 tasks	0:00:00		0:01:00	W avg
181	Tether to ORU	Done in parallel with EV1 tasks	0:00:00		0:00:29	F & W avg
182	Remove ORU from Clothesline	Done in parallel with EV1 tasks	0:00:00		0:00:28	W avg
183	Attach ORU to CETA ORU carrier	Done in parallel with EV1 tasks	0:00:00		0:01:30	Engr. est
184	Release tether to ORU	Done in parallel with EV1 tasks	0:00:00		0:00:21	F & W est
185	Translate to PFR	Done in parallel with EV1 tasks	0:00:00		0:01:00	Engr. est
186	Close ULC	Done in parallel with EV1 tasks	0:00:00		0:01:02	engr. set
187	Tether to PFR	Done in parallel with EV1 tasks	0:00:00		0:03:16	F & W avg
188	Remove PFR from socket	Done in parallel with EV1 tasks	0:00:00		0:00:00	F & W avg
189	Release clothesline & tether to clothesline end	Done in parallel with EV1 tasks	0:00:00		0:00:29	F & W avg
190	Translate to CETA	Done in parallel with EV1 tasks	0:00:00		0:01:00	Engr. est
191	Release clothesline & replace on CETA	Done in parallel with EV1 tasks	0:00:00		0:00:29	F & W avg
192	Replace PFR on CETA	Done in parallel with EV1 tasks	0:00:00		0:03:41	F & W avg
193	Release tether	Done in parallel with EV1 tasks	0:00:00		0:00:00	F & W avg
194	Ingress PFR	Done in parallel with EV1 tasks	0:00:00		0:00:28	F & W avg
195				0:00:00		
196	TRANSLATE TO WORKSITE					
197						
198	Rotate CETA for translation in opposite direction	Done in parallel with EV1 tasks	0:00:00		0:02:00	Engr. est
199	Release CETA brake	Done in parallel with EV1 tasks	0:00:00		0:00:10	Engr. est
200	Translate to port maintenance worksite	Done in parallel with EV1 tasks	0:00:00		0:01:00	Engr. est
201	Set CETA brake	Done in parallel with EV1 tasks	0:00:00		0:00:10	Engr. est
202	Egress PFR	Done in parallel with EV1 tasks	0:00:00		0:00:09	F & W avg
203				0:00:00		
204	PLACE ORU AT 2nd WORKSITE					
205						
206	Tether to clothes line	Done in parallel with EV1 tasks	0:00:00		0:00:29	F & W avg
207	Translate along truss to worksite	Done in parallel with EV1 tasks	0:00:00		0:01:00	Engr. est
208	Release clothesline tether, attach to pallet & adjust	Done in parallel with EV1 tasks	0:00:00		0:01:00	Engr. est
209	Translate to CETA	Done in parallel with EV1 tasks	0:00:00		0:01:00	Engr. est
210	Tether to ORU	Done in parallel with EV1 tasks	0:00:00		0:00:29	F & W avg
211	Release ORU from CETA	Done in parallel with EV1 tasks	0:00:00		0:00:30	Engr. est
212	Attach ORU to clothesline hook	Done in parallel with EV1 tasks	0:00:00		0:00:28	F & W avg
213	Release tether	Done in parallel with EV1 tasks	0:00:00		0:00:21	F & W avg
214	Tranfer ORU to worksite	Done in parallel with EV1 tasks	0:00:00		0:01:50	W avg
215	Translate to worksite	Done in parallel with EV1 tasks	0:00:00		0:01:00	Engr. est
216	Tether to ORU	Done in parallel with EV1 tasks	0:00:00		0:00:29	F & W avg
217	Release ORU from clothesline	Done in parallel with EV1 tasks	0:00:00		0:00:28	W avg
218	Attach ORU to pallet	Done in parallel with EV1 tasks	0:00:00		0:01:30	Engr. est
219	Release tether	Done in parallel with EV1 tasks	0:00:00		0:00:21	F & W avg
220	Release clothesline & tether to end	Done in parallel with EV1 tasks	0:00:00		0:00:29	F & W avg

	A	B	C	D	E	F
221	Translate to CETA	Done in parallel with EV1 tasks	0:00:00		0:01:00	Engr. est
222	Release clothesline & replace on CETA	Done in parallel with EV1 tasks	0:00:00		0:00:29	F & W avg
223	Ingress CETA PFR	Done in parallel with EV1 tasks	0:00:00		0:00:28	F & W avg
224	Translate to 1st worksite	Done in parallel with EV1 tasks	0:00:00		0:01:00	Engr. est
225	Egress PFR	Done in parallel with EV1 tasks	0:00:00		0:00:09	F & W avg
226	Tether to clothes line	Done in parallel with EV1 tasks	0:00:00		0:00:29	F & W avg
227	Translate to worksite	Done in parallel with EV1 tasks	0:00:00		0:01:00	Engr. est
228	Release clothesline tether, attach to pallet & adjust	Done in parallel with EV1 tasks	0:00:00		0:01:00	Engr. est
229	Translate to CETA	Done in parallel with EV1 tasks	0:00:00		0:01:00	Engr. est
230						
231					1:01:26	
232	**WORKSITE TEAR-DOWN**			0:15:56		
233						
234	EV1 egress PWP PFR		0:00:09		0:00:09	F & W avg
235	Tether to failed ORU		0:00:29		0:00:29	F & W avg
236	Release ORU from PWP		0:00:45		0:00:45	Engr. est
237	Attach ORU to clothesline hook		0:00:28		0:00:28	F & W avg
238	Release tether		0:00:21		0:00:21	F & W avg
239	Transfer ORU back to CETA	Clear path from worksite to CETA	0:01:50		0:01:50	W avg
240	EV2 tether to ORU		0:00:29		0:00:29	F & W avg
241	Release ORU from clothesline		0:00:28		0:00:28	W avg
242	Attach ORU to CETA		0:01:30		0:01:30	Engr. est
243	Release tether		0:00:21		0:00:21	F & W avg
244	EV1 tether to stanchion	Done in parallel with EV2 tasks	0:00:00		0:00:29	F & W avg
245	Release stanchion from foot restraint	Done in parallel with EV2 tasks	0:00:00		0:00:30	Engr. est
246	Attach stanchion to clothesline hook	Done in parallel with EV2 tasks	0:00:00		0:00:28	F & W avg
247	Release tether	Done in parallel with EV2 tasks	0:00:00		0:00:21	F & W avg
248	EV2 transfer stanchion to CETA		0:01:50		0:01:50	W avg
249	Tether to stanchion		0:00:29		0:00:29	F & W avg
250	Remove stanchion from clothesline hook		0:00:28		0:00:28	W avg
251	Attach stanchion to CETA		0:01:30		0:01:30	Engr. est
252	Remove tether		0:00:21		0:00:21	F & W avg
253	EV1 tether to PFR	Done in parallel with EV2 tasks	0:00:00		0:03:16	F & W avg
254	Remove PFR from socket	Done in parallel with EV2 tasks	0:00:00		0:00:00	F & W avg
255	Release clothesline & attach to tether	Done in parallel with EV2 tasks	0:00:00		0:00:29	F & W avg
256	Translate to CETA	Done in parallel with EV2 tasks	0:00:00		0:01:00	Engr. est
257	Release clothesline and replace on CETA	Partially parallel with EV2 tasks	0:00:19		0:00:29	F & W avg
258	Attach PFR to CETA		0:03:41		0:03:41	F & W avg
259	Remove tether		0:00:00		0:00:00	F & W avg
260	EV1 and EV2 ingress PFRs		0:00:28		0:00:28	F & W avg
261						
262	**TRANSLATE TO ORU CARRIER**			0:03:20		
263						
264	Rotate CETA for starboard translation		0:02:00		0:02:00	Engr. est
265	Release CETA brake		0:00:10		0:00:10	Engr. est
266	Translate to ULC		0:01:00		0:01:00	Engr. est
267	Set CETA brake		0:00:10		0:00:10	Engr. est
268						
269	**STOW ORU**			0:30:09		
270						
271	Egress PFRs		0:00:09		0:00:09	F & W avg
272	EV1 tether to PFR		0:03:16		0:03:16	F & W avg
273	Remove PFR from socket		0:00:00		0:00:00	F & W avg
274	Tether to clothesline end		0:00:29		0:00:29	F & W avg
275	Translate to ORU stowage slot		0:01:00		0:01:00	Engr. est

	A	B	C	D	E	F
276	Release clothesline, tether to ULC & adjust		0:01:00		0:01:00	Engr. est
277	Install PFR on ULC		0:03:41		0:03:41	F & W avg
278	Remove tether		0:00:00		0:00:00	F & W avg
279	Open ULC	Two latches	0:01:02		0:01:02	F avg
280	EV2 tether to ORU	Done in parallel with EV1	0:00:00		0:00:29	F & W avg
281	Release ORU from CETA	Done in parallel with EV1	0:00:00		0:00:30	Engr. est
282	Attach ORU to hook on clothesline	Done in parallel with EV1	0:00:00		0:00:28	F & W avg
283	Release tether	Done in parallel with EV1	0:00:00		0:00:21	F & W avg
284	Transfer ORU to ULC	Done in parallel with EV1	0:00:00		0:01:50	W avg
285	EV1 ingress PFR		0:00:28		0:00:28	F & W avg
286	Tether to ORU		0:00:29		0:00:29	F & W avg
287	Release ORU from clothesline hook		0:00:45		0:00:28	W avg
288	Insert ORU in stowage slot		0:01:00		0:01:00	Engr. est
289	Remove tool from MWS	Still tethered from prev. steps	0:00:26		0:00:26	F & W avg
290	Install ORU captive bolts	4 bolts	0:05:14		0:05:14	F data point
291	Attach tool to MWS		0:00:15		0:00:15	Engr. est
292	Release ORU tether		0:00:21		0:00:21	F & W avg
293	Close ULC	Two latches	0:01:02		0:01:02	Engr. est
294	Egress PFR		0:00:09		0:00:09	F & W avg
295	Tether to PFR		0:03:16		0:03:16	F & W avg
296	Release PFR from socket		0:00:00		0:00:00	F & W avg
297	Release & tether to clothesline end		0:00:29		0:00:29	F & W avg
298	Translate to CETA		0:01:00		0:01:00	Engr. est
299	Release clothesline & replace on CETA		0:00:29		0:00:29	F & W avg
300	Install PFR on CETA		0:03:41		0:03:41	F & W avg
301	Release tether		0:00:00		0:00:00	F & W avg
302	Ingress PFRs		0:00:28		0:00:28	F & W avg
303						
304	**TRANSLATE TO 2nd WORKSITE**			0:03:10		
305						
306	Rotate CETA for translation in opposite direction		0:02:00		0:02:00	Engr. est
307	Translate to 2nd worksite		0:01:00		0:01:00	Engr. est
308	Set CETA brake		0:00:10		0:00:10	Engr. est
309						
310	**WORKSITE SETUP**			0:14:44		
311						
312	EV1 egress PFR		0:00:09		0:00:09	F & W avg
313	Tether to PWP foot restraint	Crew can carry foot restraint &	0:03:16		0:03:16	F & W avg
314	Release foot restraint from CETA	clothesline at same time	0:00:00		0:00:00	F & W avg
315	Tether to clothesline end		0:00:29		0:00:29	F & W avg
316	Translate along truss to worksite	Translation along truss is allowed	0:01:00		0:01:00	Engr. est
317	Release clothesline tether, attach to pallet & adjust	Clear path from worksite to CETA	0:01:00		0:01:00	Engr. est
318	Install PWP PFR in socket	Socket available at worksite	0:03:41		0:03:41	F & W avg
319	Release tether to PFR		0:00:00		0:00:00	F & W avg
320	EV2 tether to PWP stanchion	Done in parallel with EV1 tasks	0:00:00		0:00:29	F & W avg
321	Release stanchion from CETA	Done in parallel with EV1 tasks	0:00:00		0:00:30	Engr. est
322	Attach stanchion to clothesline hook	Done in parallel with EV1 tasks	0:00:00		0:00:28	F & W avg
323	Release tether	Done in parallel with EV1 tasks	0:00:00		0:00:21	F & W avg
324	Transfer stanchion to worksite	Done in parallel with EV1 tasks	0:00:00		0:01:50	W avg
325	EV1 tether to stanchion		0:00:29		0:00:29	F & W avg
326	Release stanchion from clothesline		0:00:28		0:00:28	W avg
327	Install stanchion		0:00:42		0:00:42	F data point
328	Release tether		0:00:21		0:00:21	F & W avg
329	Tether to ORU		0:00:29		0:00:29	F & W avg
330	Release pallet tether		0:00:21		0:00:21	F & W avg

	A	B	C	D	E	F
331	Attach ORU to stanchion		0:01:30		0:01:30	Engr. est
332	Release tether		0:00:21		0:00:21	F & W avg
333	Ingress PFR		0:00:28		0:00:28	F & W avg
334						
335						
336	****PERFORM 2nd MAINTENANCE TASK****		1:00:00	1:00:00	1:00:00	
337						
338	WORKSITE TEAR-DOWN			0:15:50		
339						
340	EV1 egress PWP		0:00:09		0:00:09	F & W avg
341	Tether to failed ORU		0:00:29		0:00:29	F & W avg
342	Release ORU from PWP		0:00:45		0:00:45	Engr. est
343	Attach ORU to clothesline hook		0:00:28		0:00:28	F & W avg
344	Release tether		0:00:21		0:00:21	F & W avg
345	Transfer ORU back to CETA	Clear path from worksite to CETA	0:01:50		0:01:50	W avg
346	EV2 tether to ORU		0:00:29		0:00:29	F & W avg
347	Release ORU from clothesline		0:00:28		0:00:28	W avg
348	Attach ORU to CETA		0:01:30		0:01:30	Engr. est
349	Release tether		0:00:21		0:00:21	F & W avg
350	EV1 tether to stanchion	Done in parallel with EV2 tasks	0:00:00		0:00:29	F & W avg
351	Release stanchion from foot restraint	Done in parallel with EV2 tasks	0:00:00		0:00:30	Engr. est
352	Attach stanchion to clothesline hook	Done in parallel with EV2 tasks	0:00:00		0:00:28	F & W avg
353	Release tether	Done in parallel with EV2 tasks	0:00:00		0:00:21	F & W avg
354	EV2 transfer stanchion to CETA		0:01:50		0:01:50	W avg
355	EV2 tether to stanchion		0:00:29		0:00:29	F & W avg
356	Remove stanchion from clothesline hook		0:00:28		0:00:28	W avg
357	Attach stanchion to CETA		0:01:30		0:01:30	Engr. est
358	Remove tether		0:00:21		0:00:21	F & W avg
359	EV1 tether to PFR	Done in parallel with EV2 tasks	0:00:00		0:03:16	F & W avg
360	Remove PFR from socket	Done in parallel with EV2 tasks	0:00:00		0:00:00	F & W avg
361	Release clothesline & attach to tether	Done in parallel with EV2 tasks	0:00:00		0:00:29	F & W avg
362	Translate to CETA	Done in parallel with EV2 tasks	0:00:00		0:01:00	Engr. est
363	Release clothesline & attach to CETA	Partially parallel with EV2 tasks	0:00:13		0:00:29	F & W avg
364	Attach PFR to CETA		0:03:41		0:03:41	F & W avg
365	Remove tether		0:00:00		0:00:00	F & W avg
366	EV1 and EV2 ingress PFRs		0:00:28		0:00:28	F & W avg
367						
368	TRANSLATE TO ULC			0:03:20		
369						
370	Rotate CETA for starboard translation		0:02:00		0:02:00	Engr. est
371	Release CETA brake		0:00:10		0:00:10	Engr. est
372	Translate to ULC		0:01:00		0:01:00	Engr. est
373	Set CETA brake		0:00:10		0:00:10	Engr. est
374						
375	STOW ORU			0:29:52		
376						
377	Egress PFRs		0:00:09		0:00:09	F & W avg
378	EV1 tether to PFR		0:03:16		0:03:16	F & W avg
379	Remove PFR from socket		0:00:00		0:00:00	F & W avg
380	Tether to clothesline end		0:00:29		0:00:29	F & W avg
381	Translate to ORU stowage slot		0:01:00		0:01:00	Engr. est
382	Release clothesline, tether to ULC & adjust		0:01:00		0:01:00	Engr. est
383	Install PFR on ULC		0:03:41		0:03:41	F & W avg
384	Remove tether		0:00:00		0:00:00	F & W avg
385	Open ULC	Two latches	0:01:02		0:01:02	F avg

	A	B	C	D	E	F
386	Ingress PFR		0:00:28		0:00:28	F & W avg
387	EV2 tether to ORU	Done in parallel with EV1	0:00:00		0:00:29	F & W avg
388	Release ORU from CETA	Done in parallel with EV1	0:00:00		0:00:30	Engr. est
389	Attach ORU to hook on clothesline	Done in parallel with EV1	0:00:00		0:00:28	F & W avg
390	Release tether	Done in parallel with EV1	0:00:00		0:00:21	F & W avg
391	Transfer ORU to ULC	Done in parallel with EV1	0:00:00		0:01:50	W avg
392	Tether to ORU		0:00:29		0:00:29	F & W avg
393	EV1 release ORU from clothesline hook		0:00:28		0:00:28	W avg
394	Insert ORU in stowage slot		0:01:00		0:01:00	Engr. est
395	Remove tool from MWS		0:00:26		0:00:26	F & W avg
396	Install ORU captive bolts	4 bolts	0:05:14		0:05:14	F data point
397	Attach tool to MWS		0:00:15		0:00:15	Engr. est
398	Release tether		0:00:21		0:00:21	F & W avg
399	Close ULC		0:01:02		0:01:02	F avg
400	Egress PFR		0:00:09		0:00:09	F & W avg
401	Tether to PFR		0:03:16		0:03:16	F & W avg
402	Release PFR from socket		0:00:00		0:00:00	F & W avg
403	Release & tether to clothesline end		0:00:29		0:00:29	F & W avg
404	Translate to CETA		0:01:00		0:01:00	Engr. est
405	Release clothesline & attach to CETA		0:00:29		0:00:29	F & W avg
406	Install PFR on CETA		0:03:41		0:03:41	F & W avg
407	Release tether		0:00:00		0:00:00	F & W avg
408	Ingress PFR		0:00:28		0:00:28	F & W avg
409						
410	TRANSLATE TO AIRLOCK			0:04:29		
411						
412	Release CETA brake		0:00:10		0:00:10	Engr. est
413	Translate along CETA switching rail & pass sw. mechanism		0:00:30		0:00:30	Engr. est
414	Set CETA brake		0:00:10		0:00:10	Engr. est
415	Release rail spur deadbolt latch		0:00:15		0:00:15	Engr. est
416	Move spur/CETA to spur segment		0:00:30		0:00:30	Engr. est
417	Engage rail spur deadbolt latch		0:00:15		0:00:15	Engr. est
418	Rotate CETA for translation in opposite direction		0:02:00		0:02:00	Engr. est
419	Release CETA brake		0:00:10		0:00:10	Engr. est
420	Translate to airlock		0:00:10		0:00:10	Engr. est
421	Set CETA brake		0:00:10		0:00:10	Engr. est
422	Egress CETA PFR		0:00:09		0:00:09	F & W avg
423						
424	STOW PWP			0:09:46		
425						
426	EV1 translate to PWP stowage container		0:01:00		0:01:00	Engr. est
427	Ingress PFR		0:00:28		0:00:28	F & W avg
428	Open PWP stowage container	Two latches	0:01:02		0:01:02	F avg
429	EV2 tether to PWP stanchion	Done in parallel with EV1 tasks	0:00:00		0:00:29	F & W avg
430	Release stanchion from CETA	Done in parallel with EV1 tasks	0:00:00		0:00:30	Engr. est
431	Pass stanchion to EV1		0:00:19		0:00:19	F avg
432	EV1 tether to stanchion		0:00:29		0:00:29	F & W avg
433	EV2 release tether		0:00:21		0:00:21	F & W avg
434	EV1 install stanchion in stowage container		0:00:10		0:00:10	engr. est
435	Release tether		0:00:21		0:00:21	F & W avg
436	EV2 tether to PWP PFR	Partially parallel with EV1 tasks	0:02:45		0:03:15	F & W avg
437	Release PWP PFR from CETA	Partially parallel with EV1 tasks	0:00:00		0:00:00	F & W avg
438	Pass PWP PFR to EV1		0:00:19		0:00:19	F data point
439	EV1 tether to PWP PFR		0:00:29		0:00:29	F & W avg
440	EV2 release tether		0:00:21		0:00:21	F & W avg
441	EV1 install PFR in PWP holder		0:00:10		0:00:10	engr. est

	A	B	C	D	E	F
442	Release tether		0:00:21		0:00:21	F & W avg
443	Close PWP holder		0:01:02		0:01:02	Engr. est
444	Egress PFR		0:00:09		0:00:09	F & W avg
445	EV2 tether to clothesline	Done in parallel with EV1 tasks	0:00:00		0:00:29	F & W avg
446	Release clothesline from CETA	Done in parallel with EV1 tasks	0:00:00		0:00:29	F & W avg
447						
448	**STOW TOOLS**			0:10:33		
449						
450	Translate to toolbox on airlock	EV1 and EV2 working in parallel	0:01:00		0:01:00	Engr. est
451	Ingress PFR		0:00:28		0:00:28	F & W avg
452	Open toolbox	PFRs already there or not necessary	0:01:02		0:01:02	F avg
453	EV2 stow clothesline		0:00:20		0:00:20	engr. est
454	Release tether		0:00:21		0:00:21	F&W avg
455	Release tool from MWS		0:00:26		0:00:26	F & W avg
456	Replace power tool in toolbox		0:00:20		0:00:20	Engr. est
457	Release MWS retractable tether		0:00:21		0:00:21	F & W avg
458	Tether to tool on MWS		0:00:29		0:00:29	F & W avg
459	Release tool on MWS		0:00:26		0:00:26	F & W avg
460	Replace tool in toolbox		0:00:20		0:00:20	Engr. est
461	Release tether		0:00:21		0:00:21	F & W avg
462	Tether to MWS		0:00:29		0:00:29	F & W avg
463	Release MWS from EMU		0:00:18		0:00:18	W avg
464	Replace MWS in toolbox		0:01:15		0:01:15	W avg
465	Release tether		0:00:21		0:00:21	F & W avg
466	Close toolbox door		0:02:07		0:02:07	F avg
467	Egress PFR		0:00:09		0:00:09	F & W avg
468						
469	**INGRESS AIRLOCK**			0:09:24		
470						
471	Translate to airlock		0:01:00		0:01:00	Engr. est
472	Lock safety tethers		0:00:10		0:00:10	Engr. est
473	Replace safety tethers in pouches		0:01:00		0:01:00	Engr. est
474	EV2 enter airlock		0:06:11		0:06:11	F avg
475	EV2 secure left waist tether to airlock		0:00:00		0:00:00	F avg
476	EV1 unhook EV2s R waist tether & attach to EV1 R tether		0:00:00		0:00:00	F avg
477	EV1 unhook left waist tether		0:00:00		0:00:00	F avg
478	EV1 enter airlock		0:00:00		0:00:00	F avg
479	Close EVA hatch		0:01:03		0:01:03	F avg
480						
481						
482	••••••••••••••••••TOTAL TIME INCLUDING TWO 1 HOUR TASKS•••••••••••		5:50:44	5:50:44	8:38:49	

Appendix F

Attachment 5

	A	B	C	D	E	F
1	TASKS	ASSUMPTIONS	TASK TIME	SUMMARY TIME	PRIMITIVE	SOURCE
2						
3	EGRESS AIRLOCK			0:09:45		
4						
5	EV2 secure left waist tether to airlock	2 crewmen req'd for EVA	0:00:29		0:00:29	F&W avg
6	EV1 secure right waist tether to EV2s right waist tether		0:00:29		0:00:29	F&W avg
7	Open EVA hatch		0:08:47		0:08:47	F avg
8	EV1 exit airlock		0:00:00		0:00:00	F avg
9	EV1 secure L w-tether to CETA safety tether D-ring #1	Safety tethers secured to CETA	0:00:00		0:00:00	F avg
10	EV1 unhook EV2's R waist tether & attach to D-ring #2	Reel cases routed to airlock	0:00:00		0:00:00	F avg
11	EV2 unhook left waist tether		0:00:00		0:00:00	F avg
12	EV2 exit airlock		0:00:00		0:00:00	F avg
13	Remove safety tethers from pouches	Reel cases stowed - soft carry pouch	0:00:00		0:00:00	F avg
14	Unlock safety tethers		0:00:00		0:00:00	F avg
15						
16	ACQUIRE TOOLS			0:11:29		
17						
18	Translate to toolbox (ESE&T stowage) on airlock	PFR not necessary or already there	0:01:00		0:01:00	eng. est
19	Ingress PFR		0:00:28		0:00:28	F & W avg
20	Open toolbox door	EV1 and EV2 work in parallel	0:01:02		0:01:02	F avg
21	Tether to Mini Workstations		0:00:29		0:00:29	F&W avg
22	Release Mini Workstation from tool box		0:00:10		0:00:10	engr. est
23	Attach MWS to EMU		0:00:52		0:00:52	F avg
24	Release tether		0:00:21		0:00:21	F&W avg
25	Tether to tool (EV1 and EV2)	Two tools necessary for one task	0:01:11		0:01:11	F avg
26	Release tool from tool box		0:00:00		0:00:00	F avg
27	Attach tool to MWS		0:00:00		0:00:00	F avg
28	Release tether		0:00:00		0:00:00	F avg
29	Tether to tool		0:01:11		0:01:11	F avg
30	Release tool from toolbox		0:00:00		0:00:00	F avg
31	Attach tool to MWS	Tool remains tethered	0:00:00		0:00:00	F avg
32	EV2 tether to clothesline		0:00:29		0:00:29	F&W avg
33	Release clothesline from toolbox		0:00:10		0:00:10	engr. est
34	Close tool box		0:02:07		0:02:07	F avg
35	Egress PFR		0:00:09		0:00:09	F & W avg
36	EV2 translate to CETA		0:01:00		0:01:00	engr. est
37	Tether clothesline to CETA		0:00:29		0:00:29	F&W avg
38	Release tether		0:00:21		0:00:21	F&W avg
39						
40	TRANSLATE TO MAIN CETA RAIL			0:04:48		
41						
42	EV1 and EV2 ingress CETA PFRs		0:00:28		0:00:28	F & W avg
43	Release CETA brake		0:00:10		0:00:10	Eng. est
44	Translate along CETA rail past spur switching mechanism		0:00:10		0:00:10	Engr. est
45	Set CETA brake		0:00:10		0:00:10	Engr. est
46	Rotate CETA for translation in opposite direction		0:02:00		0:02:00	Engr. est
47	Release rail spur deadbolt latch		0:00:15		0:00:15	Engr. est
48	Move spur/CETA to main rail		0:00:30		0:00:30	Engr. est
49	Release CETA brake		0:00:15		0:00:15	Engr. est
50	Engage rail spur deadbolt latch		0:00:10		0:00:10	Engr. est
51	Translate to unpressurized logistics carrier		3:00:30		0:30:30	Engr. est
52	Set CETA brake		0:00:10		0:00:10	Engr. est
53						
54	ACQUIRE FIRST ORU			0:29:52		
55						

	A	B	C	D	E	F
56	EV1 egress PFR		0:00:09		0:00:09	F & W avg
57	Tether to PFR		0:03:16		0:03:16	F & W avg
58	Remove PFR from socket		0:00:00		0:00:00	F & W avg
59	Tether to clothesline end		0:00:29		0:00:29	F & W avg
60	Translate to ORU stowage slot	Translation along struts is	0:01:00		0:01:00	engr. est
61	Remove clothesline, attach to ULC & adjust	Attachment point available	0:01:00		0:01:00	engr. est
62	Install PFR on ULC	permissible	0:03:41		0:03:41	F & W avg
63	Remove tether		0:00:00		0:00:00	F & W avg
64	Ingress PFR		0:00:28		0:00:28	F & W avg
65	Open ULC	Two latches	0:01:02		0:01:02	F avg
66	Tether to ORU		0:00:29		0:00:29	F & W avg
67	Remove tool from MWS	Bayonet clip mount, already tethered	0:00:26		0:00:26	F & W avg
68	Remove ORU captive bolts	Four bolts	0:05:14		0:05:14	F data point
69	Attach tool to MWS		0:00:15		0:00:15	Engr. est
70	Remove ORU from stowage slot	Connectors are blind mated/demated	0:01:00		0:01:00	engr. est
71	Attach ORU to clothesline hook		0:00:28		0:00:28	F & W avg
72	Remove tether		0:00:21		0:00:21	F & W avg
73	EV2 transfer ORU to CETA		0:01:50		0:01:50	W avg
74	Tether to ORU		0:00:29		0:00:29	F & W avg
75	Remove ORU from Clothesline		0:00:28		0:00:28	W avg
76	Attach ORU to CETA ORU carrier		0:01:30		0:01:30	Engr. est
77	Release tether to ORU		0:00:21		0:00:21	F & W avg
78	EV1 close ULC	Done in parallel with EV2 tasks	0:00:00		0:01:02	engr. est
79	Egress PFR	Done in parallel with EV2 tasks	0:00:00		0:00:09	F & W avg
80	Tether to PFR	Done in parallel with EV2 tasks	0:00:00		0:03:16	F & W avg
81	Remove PFR from socket	Done in parallel with EV2 tasks	0:00:00		0:00:00	F & W avg
82	Release clothesline & tether to clothesline end	Partially parallel with EV2 tasks	0:00:18		0:00:29	F&W avg
83	Translate to CETA		0:01:00		0:01:00	engr. est
84	Release clothesline & replace on CETA		0:00:29		0:00:29	F&W avg
85	Replace PFR on CETA		0:03:41		0:03:41	F & W avg
86	Release tether		0:00:00		0:00:00	F & W avg
87	Ingress PFR		0:00:28		0:00:28	F & W avg
88						
89	**TRANSLATE TO AIRLOCK**			**0:04:29**		
90						
91	Release CETA brake		0:00:10		0:00:10	Engr. est
92	Translate along CETA switching rail & pass sw. mechanism		0:00:30		0:00:30	Engr. est
93	Set CETA brake		0:00:10		0:00:10	Engr. est
94	Release rail spur deadbolt latch		0:00:15		0:00:15	Engr. est
95	Move spur/CETA to spur segment		0:00:30		0:00:30	Engr. est
96	Engage rail spur deadbolt latch		0:00:15		0:00:15	Engr. est
97	Rotate CETA for translation in opposite direction		0:02:00		0:02:00	Engr. est
98	Release CETA brake		0:00:10		0:00:10	Engr. est
99	Translate to airlock		0:00:10		0:00:10	Engr. est
100	Set CETA brake		0:00:10		0:00:10	Engr. est
101	Egress CETA PFR		0:00:09		0:00:09	F & W avg
102						
103	**FIRST WORKSITE SETUP**			**0:10:54**		
104						
105	Egress PFR		0:00:09		0:00:09	F & W avg
106	EV2 tether to PWP foot restraint	Crew can carry foot restraint &	0:03:16		0:03:16	F & W avg
107	Release foot restraint from CETA	clothesline at same time	0:00:00		0:00:00	F & W avg
108	Translate to handrails		0:01:00		0:01:00	Engr. est
109	Attach PFR to slidewire	Done in parallel with EV2 tasks	0:00:00		0:00:45	Engr. est
110	EV1 egress PFR	Done in parallel with EV2	0:00.00		0:00:09	F & W avg

	A	B	C	D	E	F
111	Tether to ORU	Done in parallel with EV2 tasks	0:00:00		0:00:29	F & W avg
112	Release ORU from CETA	Done in parallel with EV2 tasks	0:00:00		0:00:30	Engr. est
113	Translate to handrails with ORU	Done in parallel with EV2 tasks	0:00:00		0:01:00	Engr. est
114	Attach ORU to slidewire	Done in parallel with EV2 tasks	0:00:00		0:00:45	Engr. est
115	Release tether	Done in parallel with EV2 tasks	0:00:00		0:00:21	F & W avg
116	EV1 & EV2 tether to slidewire		0:00:29		0:00:29	F & W avg
117	EV1 & EV2 release safety tethers		0:00:21		0:00:21	F & W avg
118	Stow safety tether on slidewire		0:00:30		0:00:30	Engr. est
119	Translate to worksite using handrail	/1 pushes ORU on slidewire to works	0:01:00		0:01:00	Engr. est
120	EV2 install PFR in socket	Socket available at worksite	0:03:41		0:03:41	F & W avg
121	Release tether to PFR		0:00:00		0:00:00	F & W avg
122	Ingress PFR		0:00:28		0:00:28	F & W avg
123						
124						
125	****EV1 PERFORM MAINTENANCE TASK****		1:00:00	1:00:00	1:00:00	
126						
127		RETURNS 1st ORU; OBTAINS 2nd ORU				
128	TRANSLATE TO AIRLOCK					
129				0:00:00		
130	EV2 translate to airlock using handrail	Done in parallel with EV1 tasks	0:00:00		0:01:00	Engr. est
131	Tether to safety tether	Done in parallel with EV1 tasks	0:00:00		0:00:29	F & W avg
132	Release safety tether from slidewire	Done in parallel with EV1 tasks	0:00:00		0:00:21	F & W avg
133	Translate to CETA	Done in parallel with EV1 tasks	0:00:00		0:01:00	Engr. est
134						
135	TRANSLATE TO MAIN CETA RAIL			0:00:00		
136						
137	EV2 ingress CETA PFR	Done in parallel with EV1 tasks	0:00:00		0:00:28	F & W avg
138	Release CETA brake	Done in parallel with EV1 tasks	0:00:00		0:00:10	Eng. est
139	Translate along CETA rail past spur switching mechanism	Done in parallel with EV1 tasks	0:00:00		0:00:10	Engr. est
140	Set CETA brake	Done in parallel with EV1 tasks	0:00:00		0:00:10	Engr. est
141	Rotate CETA for translation in opposite direction	Done in parallel with EV1 tasks	0:00:00		0:02:00	Engr. est
142	Release rail spur deadbolt latch	Done in parallel with EV1 tasks	0:00:00		0:00:15	Engr. est
143	Move spur/CETA to main rail	Done in parallel with EV1 tasks	0:00:00		0:00:30	Engr. est
144	Release CETA brake	Done in parallel with EV1 tasks	0:00:00		0:00:15	Engr. est
145	Engage rail spur deadbolt latch	Done in parallel with EV1 tasks	0:00:00		0:00:10	Engr. est
146	Translate to unpressurized logistics carrier	Done in parallel with EV1 tasks	0:00:00		0:00:30	Engr. est
147	Set CETA brake	Done in parallel with EV1 tasks	0:00:00		0:00:10	Engr. est
148						
149	ACQUIRE ORU			0:00:00		
150						
151	EV2 egress PFR	Done in parallel with EV2	0:00:00		0:00:09	F & W avg
152	Tether to PFR	Done in parallel with EV1 tasks	0:00:00		0:03:16	F & W avg
153	Remove PFR from socket	Done in parallel with EV1 tasks	0:00:00		0:00:00	F & W avg
154	Tether to clothesline end	Done in parallel with EV1 tasks	0:00:00		0:00:29	F & W avg
155	Translate to ORU stowage slot	Done in parallel with EV1 tasks	0:00:00		0:01:00	Engr. est
156	Remove Clothesline, attach to ULC & adjust	Done in parallel with EV1 tasks	0:00:00		0:01:00	engr. est
157	Install PFR on ULC	Done in parallel with EV1 tasks	0:00:00		0:03:41	F & W avg
158	Remove tether	Done in parallel with EV1 tasks	0:00:00		0:00:00	F & W avg
159	Ingress PFR	Done in parallel with EV1 tasks	0:00:00		0:00:28	F & W avg
160	Open ULC	Done in parallel with EV1 tasks	0:00:00		0:01:02	
161	Tether to 2nd ORU	Done in parallel with EV1 tasks	0:00:00		0:00:29	F & W avg
162	Remove tool from MWS	Done in parallel with EV1 tasks	0:00:00		0:00:26	F & W avg
163	Remove ORU captive bolts	Done in parallel with EV1 tasks	0:00:00		0:05:14	F data point
164	Attach tool to MWS	Done in parallel with EV1 tasks	0:00:00		0:00:15	Engr. est
165	Remove ORU from stowage slot	Done in parallel with EV1 tasks	0:00:00		0:01:00	Engr. est

	A	B	C	D	E	F
166	Attach ORU to clothesline hook	Done in parallel with EV1 tasks	0:00:00		0:00:28	F & W avg
167	Remove tether	Done in parallel with EV1 tasks	0:00:00		0:00:21	F & W avg
168	Transfer ORU to CETA	Done in parallel with EV1 tasks	0:00:00		0:01:50	W avg
169	Egress PFR	Done in parallel with EV1 tasks	0:00:00		0:00:09	F & W avg
170	Translate to CETA	Done in parallel with EV1 tasks	0:00:00		0:01:00	W avg
171	Tether to ORU	Done in parallel with EV1 tasks	0:00:00		0:00:29	F & W avg
172	Remove ORU from Clothesline	Done in parallel with EV1 tasks	0:00:00		0:00:28	W avg
173	Attach ORU to CETA ORU carrier	Done in parallel with EV1 tasks	0:00:00		0:01:30	Engr. est
174	Release tether to ORU	Done in parallel with EV1 tasks	0:00:00		0:00:21	F & W est
175	Translate to PFR	Done in parallel with EV1 tasks	0:00:00		0:01:00	Engr. est
176	Close ULC	Done in parallel with EV1 tasks	0:00:00		0:01:02	engr. set
177	Tether to PFR	Done in parallel with EV1 tasks	0:00:00		0:03:16	F & W avg
178	Remove PFR from socket	Done in parallel with EV1 tasks	0:00:00		0:00:00	F & W avg
179	Release clothesline & tether to clothesline end	Done in parallel with EV1 tasks	0:00:00		0:00:29	F & W avg
180	Translate to CETA	Done in parallel with EV1 tasks	0:00:00		0:01:00	Engr. est
181	Release clothesline & replace on CETA	Done in parallel with EV1 tasks	0:00:00		0:00:29	F & W avg
182	Replace PFR on CETA	Done in parallel with EV1 tasks	0:00:00		0:03:41	F & W avg
183	Release tether	Done in parallel with EV1 tasks	0:00:00		0:00:00	F & W avg
184	Ingress PFR	Done in parallel with EV1 tasks	0:00:00		0:00:28	F & W avg
185						
186	**TRANSLATE TO AIRLOCK**			0:00:00		
187						
188	Release CETA brake	Done in parallel with EV1 tasks	0:00:00		0:00:10	Engr. est
189	Translate along CETA switching rail & pass sw. mechanism	Done in parallel with EV1 tasks	0:00:00		0:00:30	Engr. est
190	Set CETA brake	Done in parallel with EV1 tasks	0:00:00		0:00:10	Engr. est
191	Release rail spur deadbolt latch	Done in parallel with EV1 tasks	0:00:00		0:00:15	Engr. est
192	Move spur/CETA to spur segment	Done in parallel with EV1 tasks	0:00:00		0:00:30	Engr. est
193	Engage rail spur deadbolt latch	Done in parallel with EV1 tasks	0:00:00		0:00:15	Engr. est
194	Rotate CETA for translation in opposite direction	Done in parallel with EV1 tasks	0:00:00		0:02:00	Engr. est
195	Release CETA brake	Done in parallel with EV1 tasks	0:00:00		0:00:10	Engr. est
196	Translate to airlock	Done in parallel with EV1 tasks	0:00:00		0:00:10	Engr. est
197	Set CETA brake	Done in parallel with EV1 tasks	0:00:00		0:00:10	Engr. est
198	Egress CETA PFR	Done in parallel with EV1 tasks	0:00:00		0:00:09	F & W avg
199						
200	**PLACE ORU AT 2nd WORKSITE**			0:00:00		
201						
202	Tether to ORU	Done in parallel with EV1 tasks	0:00:00		0:00:29	F & W avg
203	Release ORU from CETA	Done in parallel with EV1 tasks	0:00:00		0:00:30	Engr. est
204	Translate to handrails with ORU	Done in parallel with EV1 tasks	0:00:00		0:01:00	Engr. est
205	Attach ORU to slidewire	Done in parallel with EV1 tasks	0:00:00		0:00:45	F & W avg
206	Release tether	Done in parallel with EV1 tasks	0:00:00		0:00:21	F & W avg
207	Tether to slidewire	Done in parallel with EV1 tasks	0:00:00		0:00:29	F & W avg
208	Release safety tethers	Done in parallel with EV1 tasks	0:00:00		0:00:21	F & W avg
209	Stow safety tether on slidewire	Done in parallel with EV1 tasks	0:00:00		0:00:30	Engr. est
210	Translate to 2nd worksite using handrail	Done in parallel with EV1 tasks	0:00:00		0:01:00	Engr. est
211	EV2 translate to airlock on handrails				0:01:00	Engr. est
212	Tether to safety tether	Done in parallel with EV2 tasks	0:00:00		0:00:29	F & W avg
213	Release safety tether from slidewire	Done in parallel with EV1 tasks	0:00:00		0:00:21	F & W avg
214	Translate to 1st set of handrails	Done in parallel with EV1 tasks	0:00:00		0:01:00	Engr. est
215	Tether to slidewire	Done in parallel with EV1 tasks	0:00:00		0:00:29	F & W avg
216	Release safety tethers	Done in parallel with EV1 tasks	0:00:00		0:00:21	F & W avg
217	Stow safety tether on slidewire	Done in parallel with EV1 tasks	0:00:00		0:00:30	Engr. est
218	Translate to 1st worksite on handrails	Done in parallel with EV1 tasks	0:00:00		0:01:00	Engr. est
219						
220	FIRST WORKSITE TEAR-DOWN			0:08:40		

	A	B	C	D	E	F
221						
222	EV1 tether to PFR		0:03:16		0:03:16	F & W avg
223	Remove PFR from socket		0:00:00		0:00:00	F & W avg
224	Attach PFR to slidewire		0:00:45		0:00:45	Engr. est
225	Release tether		0:00:21		0:00:21	F & W avg
226	EV1 and EV2 translate to airlock on handrails		0:01:00		0:01:00	Engr. est
227	Tether to safety tether		0:00:29		0:00:29	F & W avg
228	Release safety tether from slidewire		0:00:21		0:00:21	F & W avg
229	EV1 tether to foot restraint		0:00:29		0:00:29	F & W avg
230	EV1 release foot restraint from slidewire		0:00:45		0:00:45	Engr. est
231	EV2 tether to ORU	Done in parallel with EV1 tasks	0:00:29		0:00:29	F & W avg
232	Release ORU from slidewire	Done in parallel with EV1 tasks	0:00:45		0:00:45	Engr. est
233						
234	**TRANSLATE TO 2nd WORKSITE**			**0:03:20**		
235						
236	EV1 translate to handrails		0:01:00		0:01:00	Engr. est
237	Attach PFR to slidewire	Done in parallel with EV2 tasks	0:00:00		0:00:45	Engr. est
238	Release tether	Done in parallel with EV2 tasks	0:00:00		0:00:21	F & W avg
239	Tether to slidewire		0:00:29		0:00:29	F & W avg
240	Release safety tethers		0:00:21		0:00:21	F & W avg
241	Stow safety tether on slidewire		0:00:30		0:00:30	Engr. est
242	Translate to 2nd worksite using handrail	V1 pushes ORU on slidewire to worksi	0:01:00		0:01:00	Engr. est
243						
244	**WORKSITE SETUP**			**0:08:10**		
245						
246	EV1 tether to foot restraint	Crew can carry foot restraint &	0:03:16		0:03:16	F & W avg
247	Release foot restraint from slidewire		0:00:45		0:00:45	Engr. est
248	Install PFR in socket	Socket available at worksite	0:03:41		0:03:41	F & W avg
249	Release tether to PFR		0:00:00		0:00:00	F & W avg
250	Ingress PFR		0:00:28		0:00:28	F & W avg
251						
252						
253	****PERFORM 2nd MAINTENANCE TASK****		**1:00:00**	**1:00:00**	**1:00:00**	
254						
255						
256	**TRANSLATE TO MAIN CETA RAIL**			**0:00:00**		
257						
258	EV2 translate to CETA	Done in parallel with EV1 tasks	0:00:00		0:01:00	Engr. est
259	Attach ORU to CETA	Done in parallel with EV1 tasks	0:00:00		0:01:30	Engr. est
260	Release tether	Done in parallel with EV1 tasks	0:00:00		0:00:21	F & W avg
261	Ingress CETA PFR	Done in parallel with EV1 tasks	0:00:00		0:00:28	F & W avg
262	Release CETA brake	Done in parallel with EV1 tasks	0:00:00		0:00:10	Eng. est
263	Translate along CETA rail past spur switching mechanism	Done in parallel with EV1 tasks	0:00:00		0:00:10	Engr. est
264	Set CETA brake	Done in parallel with EV1 tasks	0:00:00		0:00:10	Engr. est
265	Rotate CETA for translation in opposite direction	Done in parallel with EV1 tasks	0:00:00		0:02:00	Engr. est
266	Release rail spur deadbolt latch	Done in parallel with EV1 tasks	0:00:00		0:00:15	Engr. est
267	Move spur/CETA to main rail	Done in parallel with EV1 tasks	0:00:00		0:00:30	Engr. est
268	Release CETA brake	Done in parallel with EV1 tasks	0:00:00		0:00:15	Engr. est
269	Engage rail spur deadbolt latch	Done in parallel with EV1 tasks	0:00:00		0:00:10	Engr. est
270	Translate to unpressurized logistics carrier	Done in parallel with EV1 tasks	0:00:00		0:00:30	Engr. est
271	Set CETA brake	Done in parallel with EV1 tasks	0:00:00		0:00:10	Engr. est
272						
273	STOW 2nd ORU			0:00:00		
274						
275	EV2 egress PFR	Done in parallel with EV2	0:00:00		0:00:09	F & W avg

	A	B	C	D	E	F
276	Tether to PFR	Done in parallel with EV1 tasks	0:00:00		0:03:16	F & W avg
277	Remove PFR from socket	Done in parallel with EV1 tasks	0:00:00		0:00:00	F & W avg
278	Tether to clothesline end	Done in parallel with EV1 tasks	0:00:00		0:00:29	F & W avg
279	Translate to ORU stowage slot	Done in parallel with EV1 tasks	0:00:00		0:01:00	Engr. est
280	Remove Clothesline, attach to ULC & adjust	Done in parallel with EV1 tasks	0:00:00		0:01:00	engr. est
281	Install PFR on ULC	Done in parallel with EV1 tasks	0:00:00		0:03:41	F & W avg
288	Release tether	Done in parallel with EV1 tasks	0:00:00		0:00:00	F & W avg
289	Translate to CETA	Done in parallel with EV1 tasks	0:00:00		0:01:00	W avg
290	Tether to ORU	Done in parallel with EV1 tasks	0:00:00		0:00:29	F & W avg
291	Release ORU from CETA	Done in parallel with EV1	0:00:00		0:00:30	Engr. est
292	Attach ORU to hook on clothesline	Done in parallel with EV1	0:00:00		0:00:28	F & W avg
293	Release tether	Done in parallel with EV1	0:00:00		0:00:21	F & W avg
294	Transfer ORU to ULC	Done in parallel with EV1	0:00:00		0:01:50	W avg
295	Translate to ULC	Done in parallel with EV1 tasks	0:00:00		0:01:00	W avg
296	Open ULC	Done in parallel with EV1 tasks	0:00:00		0:01:02	F & W avg
297	Ingress PFR	Done in parallel with EV1 tasks	0:00:00		0:00:28	F & W avg
298	Tether to ORU	Done in parallel with EV1 tasks	0:00:00		0:00:29	F & W avg
299	Remove ORU from Clothesline	Done in parallel with EV1 tasks	0:00:00		0:00:28	W avg
300	Install ORU in ULC	Done in parallel with EV1 tasks	0:00:00		0:01:00	Engr. est
301	Remove tool from MWS	Done in parallel with EV1 tasks	0:00:00		0:00:26	F & W avg
302	Install ORU captive bolts	Done in parallel with EV1 tasks	0:00:00		0:05:14	F data point
303	Attach tool to MWS	Done in parallel with EV1 tasks	0:00:00		0:00:15	Engr. est
304	Egress PFR	Done in parallel with EV1 tasks	0:00:00		0:00:09	F & W avg
305	Close ULC	Done in parallel with EV1 tasks	0:00:00		0:01:02	engr. set
306	Tether to PFR	Done in parallel with EV1 tasks	0:00:00		0:03:16	F & W avg
307	Remove PFR from socket	Done in parallel with EV1 tasks	0:00:00		0:00:00	F & W avg
308	Release clothesline & tether to clothesline end	Done in parallel with EV1 tasks	0:00:00		0:00:29	F & W avg
309	Translate to CETA	Done in parallel with EV1 tasks	0:00:00		0:01:00	Engr. est
310	Release clothesline & replace on CETA	Done in parallel with EV1 tasks	0:00:00		0:00:29	F & W avg
311	Replace PFR on CETA	Done in parallel with EV1 tasks	0:00:00		0:03:41	F & W avg
312	Release tether	Done in parallel with EV1 tasks	0:00:00		0:00:00	F & W avg
313	Ingress PFR	Done in parallel with EV1 tasks	0:00:00		0:00:28	F & W avg
314						
315	**TRANSLATE TO AIRLOCK**			0:00:00		
316						
317	Release CETA brake	Done in parallel with EV1 tasks	0:00:00		0:00:10	Engr. est
318	Translate along CETA switching rail & pass sw. mechanism	Done in parallel with EV1 tasks	0:00:00		0:00:30	Engr. est
319	Set CETA brake	Done in parallel with EV1 tasks	0:00:00		0:00:10	Engr. est
320	Release rail spur deadbolt latch	Done in parallel with EV1 tasks	0:00:00		0:00:15	Engr. est
321	Move spur/CETA to spur segment	Done in parallel with EV1 tasks	0:00:00		0:00:30	Engr. est
322	Engage rail spur deadbolt latch	Done in parallel with EV1 tasks	0:00:00		0:00:15	Engr. est
323	Rotate CETA for translation in opposite direction	Done in parallel with EV1 tasks	0:00:00		0:02:00	Engr. est
324	Release CETA brake	Done in parallel with EV1 tasks	0:00:00		0:00:10	Engr. est
325	Translate to airlock	Done in parallel with EV1 tasks	0:00:00		0:00:10	Engr. est
326	Set CETA brake	Done in parallel with EV1 tasks	0:00:00		0:00:10	Engr. est
327	Egress CETA PFR	Done in parallel with EV1 tasks	0:00:00		0:00:09	F & W avg
328						
329						
330	**TRANSLATE TO 2nd WORKSITE**			0:00:00		
331						
332	Translate to handrails		0:00:00		0:01:00	Engr. est
333	Tether to slidewire	Done in parallel with EV1 tasks	0:00:00		0:00:29	F & W avg
334	Release safety tethers	Done in parallel with EV1 tasks	0:00:00		0:00:21	F & W avg
335	Stow safety tether on slidewire	Done in parallel with EV1 tasks	0:00:00		0:00:30	Engr. est
336	Translate to 2nd worksite using handrail	Done in parallel with EV1 tasks	0:00:00		0:01:00	Engr. est
337						

	A	B	C	D	E	F
338	2nd WORKSITE TEAR-DOWN			0:12:35		
339						
340	EV1 tether to PFR		0:03:16		0:03:16	F & W avg
341	Remove PFR from socket		0:00:00		0:00:00	F & W avg
342	Attach PFR to slidewire		0:00:45		0:00:45	Engr. est
343	Release tether		0:00:21		0:00:21	F & W avg
344	EV1 and EV2 translate to airlock on handrails		0:01:00		0:01:00	Engr. est
345	Tether to safety tether		0:00:29		0:00:29	F & W avg
346	Release safety tether from slidewire		0:00:21		0:00:21	F & W avg
347	EV1 tether to foot restraint		0:00:29		0:00:29	F & W avg
348	EV1 release foot restraint from slidewire		0:00:45		0:00:45	Engr. est
349	EV2 tether to ORU	Done in parallel with EV1 tasks	0:00:00		0:00:29	F & W avg
350	Release ORU from slidewire	Done in parallel with EV1 tasks	0:00:00		0:00:45	Engr. est
351	EV1 and EV2 translate to CETA		0:01:00		0:01:00	Engr. est
352	EV1 install PFR on CETA		0:03:41		0:03:41	F & W avg
353	Release tether		0:00:00		0:00:00	F & W avg
354	EV2 attach ORU to CETA	Done in parallel with EV1 tasks	0:00:00			
355	Release tether	Done in parallel with EV1 tasks	0:00:00			
356	EV1 and EV2 ingress PFRs		0:00:28		0:00:28	F & W avg
357						
358	TRANSLATE TO MAIN CETA RAIL			0:04:48		
359						
360	EV1 and EV2 ingress CETA PFRs		0:00:28		0:00:28	F & W avg
361	Release CETA brake		0:00:10		0:00:10	Eng. est
362	Translate along CETA rail past spur switching mechanism		0:00:10		0:00:10	Engr. est
363	Set CETA brake		0:00:10		0:00:10	Engr. est
364	Rotate CETA for translation in opposite direction		0:02:00		0:02:00	Engr. est
365	Release rail spur deadbolt latch		0:00:15		0:00:15	Engr. est
366	Move spur/CETA to main rail		0:00:30		0:00:30	Engr. est
367	Release CETA brake		0:00:15		0:00:15	Engr. est
368	Engage rail spur deadbolt latch		0:00:10		0:00:10	Engr. est
369	Translate to unpressurized logistics carrier		0:00:30		0:00:30	Engr. est
370	Set CETA brake		0:00:10		0:00:10	Engr. est
371						
372	TRANSLATE TO ULC			0:03:20		
373						
374	Rotate CETA for starboard translation		0:02:00		0:02:00	Engr. est
375	Release CETA brake		0:00:10		0:00:10	Engr. est
376	Translate to ULC		0:01:00		0:01:00	Engr. est
377	Set CETA brake		0:00:10		0:00:10	Engr. est
378						
379	STOW ORU			0:29:52		
380						
381	Egress PFRs		0:00:09		0:00:09	F & W avg
382	EV1 tether to PFR		0:03:16		0:03:16	F & W avg
383	Remove PFR from socket		0:00:00		0:00:00	F & W avg
384	Tether to clothesline end		0:00:29		0:00:29	F & W avg
385	Translate to ORU stowage slot		0:01:00		0:01:00	Engr. est
386	Release clothesline, tether to ULC & adjust		0:01:00		0:01:00	Engr. est
387	Install PFR on ULC		0:03:41		0:03:41	F & W avg
388	Remove tether		0:00:00		0:00:00	F & W avg
389	Open ULC	Two latches	0:01:02		0:01:02	F avg
390	Ingress PFR		0:00:28		0:00:28	F & W avg
391	EV2 tether to ORU	Done in parallel with EV1	0:00:00		0:00:29	F & W avg
392	Release ORU from CETA	Done in parallel with EV1	0:00:00		0:00:30	Engr. est

	A	B	C	D	E	F
393	Attach ORU to hook on clothesline	Done in parallel with EV1	0:00:00		0:00:28	F & W avg
394	Release tether	Done in parallel with EV1	0:00:00		0:00:21	F & W avg
395	Transfer ORU to ULC	Done in parallel with EV1	0:00:00		0:01:50	W avg
396	Tether to ORU		0:00:29		0:00:29	F & W avg
397	EV1 release ORU from clothesline hook		0:00:28		0:00:28	W avg
398	Insert ORU in stowage slot		0:01:00		0:01:00	Engr. est
399	Remove tool from MWS		0:00:26		0:00:26	F & W avg
400	Install ORU captive bolts	4 bolts	0:05:14		0:05:14	F data point
401	Attach tool to MWS		0:00:15		0:00:15	Engr. est
402	Release tether		0:00:21		0:00:21	F & W avg
403	Close ULC		0:01:02		0:01:02	F avg
404	Egress PFR		0:00:09		0:00:09	F & W avg
405	Tether to PFR		0:03:16		0:03:16	F & W avg
406	Release PFR from socket		0:00:00		0:00:00	F & W avg
407	Release & tether to clothesline end		0:00:29		0:00:29	F & W avg
408	Translate to CETA		0:01:00		0:01:00	Engr. est
409	Release clothesline & attach to CETA		0:00:29		0:00:29	F & W avg
410	Install PFR on CETA		0:03:41		0:03:41	F & W avg
411	Release tether		0:00:00		0:00:00	F & W avg
412	Ingress PFR		0:00:28		0:00:28	F & W avg
413						
414	**TRANSLATE TO AIRLOCK**			0:04:29		
415						
416	Release CETA brake		0:00:10		0:00:10	Engr. est
417	Translate along CETA switching rail & pass sw. mechanism		0:00:30		0:00:30	Engr. est
418	Set CETA brake		0:00:10		0:00:10	Engr. est
419	Release rail spur deadbolt latch		0:00:15		0:00:15	Engr. est
420	Move spur/CETA to spur segment		0:00:30		0:00:30	Engr. est
421	Engage rail spur deadbolt latch		0:00:15		0:00:15	Engr. est
422	Rotate CETA for translation in opposite direction		0:02:00		0:02:00	Engr. est
423	Release CETA brake		0:00:10		0:00:10	Engr. est
424	Translate to airlock		0:00:10		0:00:10	Engr. est
425	Set CETA brake		0:00:10		0:00:10	Engr. est
426	Egress CETA PFR		0:00:09		0:00:09	F & W avg
427						
428	**STOW TOOLS**			0:10:33		
429						
430	Translate to toolbox on airlock	EV1 and EV2 working in parallel	0:01:00		0:01:00	Engr. est
431	Ingress PFR		0:00:28		0:00:28	F & W avg
432	Open toolbox	PFRs already there or not necessary	0:01:02		0:01:02	F avg
433	EV2 stow clothesline		0:00:20		0:00:20	engr. est
434	Release tether		0:00:21		0:00:21	F&W avg
435	Release tool from MWS		0:00:26		0:00:26	F & W avg
436	Replace power tool in toolbox		0:00:20		0:00:20	Engr. est
437	Release MWS retractable tether		0:00:21		0:00:21	F & W avg
438	Tether to tool on MWS		0:00:29		0:00:29	F & W avg
439	Release tool on MWS		0:00:26		0:00:26	F & W avg
440	Replace tool in toolbox		0:00:20		0:00:20	Engr. est
441	Release tether		0:00:21		0:00:21	F & W avg
442	Tether to MWS		0:00:29		0:00:29	F & W avg
443	Release MWS from EMU		0:00:18		0:00:18	W avg
444	Replace MWS in toolbox		0:01:15		0:01:15	W avg
445	Release tether		0:00:21		0:00:21	F & W avg
446	Close toolbox door		0:02:07		0:02:07	F avg
447	Egress PFR		0:00:09		0:00:09	F & W avg
448						

	A	B	C	D	E	F
449	**INGRESS AIRLOCK**			0:09:24		
450						
451	Translate to airlock		0:01:00		0:01:00	Engr. est
452	Lock safety tethers		0:00:10		0:00:10	Engr. est
453	Replace safety tethers in pouches		0:01:00		0:01:00	Engr. est
454	EV2 enter airlock		0:06:11		0:06:11	F avg
455	EV2 secure left waist tether to airlock		0:00:00		0:00:00	F avg
456	EV1 unhook EV2s R waist tether & attach to EV1 R tether		0:00:00		0:00:00	F avg
457	EV1 unhook left waist tether		0:00:00		0:00:00	F avg
458	EV1 enter airlock		0:00:00		0:00:00	F avg
459	Close EVA hatch		0:01:03		0:01:03	F avg
460						
461						
462	******************TOTAL TIME INCLUDING TWO 1 HOUR TASKS******		4:46:28	4:46:28	6:53:39	

Appendix F

Attachment 6

	A	B	C	D	E	P
1	TASKS	ASSUMPTIONS	SUBTASK TIME	TASK TIME	SOURCE	PRIMITIVE
2						
3	EGRESS AIRLOCK			0:11:45		
4						
5	EV2 secure left waist tether to airlock	2 crewmen req'd for EVA	0:00:29		F&W avg	0:00:29
6	EV1 secure right waist tether to EV2s right waist tether		0:00:29		F&W avg	0:00:29
7	Open EVA hatch		0:08:47		F avg	0:08:47
8	EV1 exit airlock		0:00:00		F avg	0:00:00
9	EV1 secure L w-tether to CETA safety tether D-ring #1	Safety tethers secured to CETA	0:00:00		F avg	0:00:00
10	EV1 unhook EV2's R waist tether & attach to D-ring #2	Reel cases routed to airlock	0:00:00		F avg	0:00:00
11	EV2 unhook left waist tether		0:00:00		F avg	0:00:00
12	EV2 exit airlock		0:00:00		F avg	0:00:00
13	Remove safety tethers from pouches	Reel cases stowed - soft carry pouch	0:00:00		F avg	0:00:00
14	Unlock safety tethers		0:00:00		F avg	0:00:00
15	Follow safety tether lines to CETA & release restraints	Restraints req'd for line mgmt	0:02:00		engr. est	0:02:00
16						
17						
18	ACQUIRE TOOLS			0:06:12		
19		Crewmembers begin working in parallel				
20						
21	Open toolbox door	Toolbox stowed on CETA	0:01:02		F avg	0:01:02
22	Tether to Mini Workstations	MWS stowed in toolbox	0:00:29		F&W avg	0:00:30
23	Release Mini Workstation from tool box		0:00:10		engr. est	0:00:10
24	Attach MWS to EMU		0:00:52		F avg	0:00:52
25	Release tether		0:00:21		F&W avg	0:00:22
26	Tether to power tool (EV1 and EV2)	Two tools necessary for one task	0:01:11		F avg	0:01:04
27	Release tool from tool box		0:00:00		F avg	0:00:00
28	Attach tool to MWS		0:00:00		F avg	0:00:00
29	Close tool box		0:02:07		F avg	0:02:07
30						
31	TRANSLATE TO ULC			0:01:28		
32						
33	Ingress CETA PFR		0:00:28		F & W avg	0:00:28
34	Release CETA brake		0:00:10		Eng. est	0:00:10
35	Translate along CETA rail along airlock spur		0:00:10		Engr. est	0:00:10
36	Translate to unpressurized logistics carrier	Carrier located on way to worksite	0:00:30		Engr. est	0:00:30
37	Set CETA brake		0:00:10		Engr. est	0:00:10
38						
39	ACQUIRE ORU			0:25:14		
40						
41	Egress CETA PFRs		0:00:09		F & W avg	0:00:09
42	Ingress ULC foot restraint		0:00:28		F & W avg	0:00:28
43	Open ULC	CETA provides adequate access to UPLC	0:01:02		F avg	0:01:02
44	Tether to ORU	Transport device available	0:00:29		F & W avg	0:00:29
45	Open launch restraint latches		0:01:00		Engr. est	0:01:00
46	Remove ORU from stowage slot	Connectors are blind mated/demated	0:01:00		Engr. est	0:01:00
47	Rotate to CETA		0:00:30		Engr. est	0:00:30
48	Attach ORU to CETA ORU carrier	ORU remains attached to trans.	0:01:30		Engr. est	0:01:30
49	Release tether		0:00:21		F & W avg	0:00:21
50	Close ULC		0:01:02			0:01:02
51	Egress ULC foot restraint		0:00:09		F & W avg	0:00:09
52	Ingress CETA PFR		0:00:28		F & W avg	0:00:28
53	Release CETA brake		0:00:10		Engr est	0:00:10
54	Translate to second stowage location		0:00:20		Engr. est	0:00:20
55	Set CETA brake		0:00:10		Engr. est	0:00:10
56	Egress PFR		0:00:09		F & W avg	0:00:09

	A	B	C	D	E	P
57	Ingress ULC foot restraint		0:00:28		F & W avg	0:00:28
58	Open ULC		0:01:02		F & W avg	0:01:02
59	Tether to ORU	Transport device available	0:00:29		F & W avg	0:00:29
60	Open launch restraint latches		0:01:00		Engr. est	0:01:00
61	Remove ORU from stowage slot	Connectors are blind mated/demated	0:01:00		Engr. est	0:01:00
62	Rotate to CETA		0:00:30		Engr. est	0:00:30
63	Attach ORU to CETA ORU carrier		0:01:30		Engr. est	0:01:30
64	Release tether		0:00:21		F & W avg	0:00:21
65	Close ULC		0:01:02		F & W avg	0:01:02
66	Egress ULC foot restraint		0:00:09		F & W avg	0:00:09
67	Ingress CETA PFR		0:00:28		F & W avg	0:00:28
68	Release CETA brake		0:00:10		Engr. est	0:00:10
69	Translate to third stowage location		0:00:20		Engr. est	0:00:20
70	Set CETA brake		0:00:10		Engr. est	0:00:10
71	Egress PFR		0:00:09		F & W avg	0:00:09
72	Ingress ULC foot restraint		0:00:28		F & W avg	0:00:28
73	Open ULC		0:01:02		F & W avg	0:01:02
74	Tether to ORU	Transport device available	0:00:29		F & W avg	0:00:29
75	Open launch restraint latches		0:00:30		Engr. est	0:00:30
76	Remove ORU from stowage slot	Connectors are blind mated/demated	0:01:00		Engr. est	0:01:00
77	Rotate to CETA		0:00:30		Engr. est	0:00:30
78	Attach ORU to CETA ORU carrier		0:01:30		Engr. est	0:01:30
79	Release tether		0:00:21		F & W avg	0:00:21
80	Close ULC	two latches similar to CBSA	0:01:02		F & W avg	0:01:02
81	Egress ULC foot restraint		0:00:09		F & W avg	0:00:09
82	Ingress CETA PFR		0:00:28		F & W avg	0:00:28
83						
84	TRANSLATE TO WORKSITE			0:01:29		
85						
86	Release CETA brake		0:00:10		Engr. est	0:00:10
87	Translate to port maintenance worksite	Inboard of alpha joint	0:01:00		Engr. est	0:01:00
88	Set CETA brake		0:00:10		Engr. est	0:00:10
89	Egress PFR		0:00:09		F & W avg	0:00:09
90						
91	WORKSITE SETUP			0:06:01		
92						
93	Attach ORU to transfer device		0:00:45		W avg	0:00:45
94	Release ORU from CETA		0:01:50		W avg	0:01:50
95	Transfer ORU to worksite		0:01:00		Engr. est	0:01:00
96	Translate along truss to worksite		0:01:30		Engr. est	0:01:30
97	Attach ORU to PWP	PWP not necessary or already set up a	0:00:28		W avg	0:00:28
98	Release ORU from transfer device		0:00:28		F & W avg	0:00:28
99	Ingress PFR					
100						
101	****PERFORM MAINTENANCE TASK****		1:00:00	1:00:00		1:00:00
102						
103	WORKSITE TEARDOWN			0:06:42		
104						
105	EV1 egress PWP PFR		0:00:09		F & W avg	0:00:09
106	Attach ORU/PWP to transfer device		0:00:45		F & W avg	0:00:45
107	Transfer ORU/PWP back to CETA	Clear path from worksite to CETA	0:01:50		W avg	0:01:50
108	Translate to CETA	Translation along truss is allowed	0:01:00		Engr. est	0:01:00
109	Attach ORU to CETA		0:01:30		F & W avg	0:01:30
110	Release ORU from PWP		0:00:45		Engr. est	0:00:45
111	Attach PWP to CETA		0:01:30		F & W avg	0:01:30
112	Release ORU from PWP		0:00:45		W avg	0:00:45

	A	B	C	D	E	P
113	Ingress PFR		0:00:28		F & W avg	0:00:28
114						
115	TRANSLATE TO 2nd WORKSITE			0:01:29		
116						
117	Release CETA brake		0:00:10		Engr. est	0:00:10
118	Translate to 2nd maintenance worksite	Inboard of alpha joint	0:01:00		Engr. est	0:01:00
119	Set CETA brake		0:00:10		Engr. est	0:00:10
120	Egress PFR		0:00:09		F & W avg	0:00:09
121						
122	2nd WORKSITE SETUP			0:14:27		
123						
124	Attach 2nd ORU to transfer device		0:00:45		F & W avg	0:00:45
125	Release ORU from CETA		0:00:30		Engr. est	0:00:30
126	Release PWP PFR from CETA	Includes tether time	0:03:16		F & W avg	0:03:16
127	Tranfer ORU & PWP to worksite		0:01:50		W avg	0:01:50
128	Translate to pallet	Translation along truss is allowed	0:01:00		Engr. est	0:01:00
129	Install PWP PFR in socket	Socket available at worksite	0:03:22		F & W avg	0:03:22
130	Release PWP from transfer device		0:00:00		W avg	0:00:00
131	Tether ORU to PWP	Crew can carry foot restraint &	0:03:16		F & W avg	0:03:16
132	Release ORU from transfer device		0:00:00		W avg	0:00:00
133	Ingress PWP		0:00:28		F & W avg	0:00:28
134						
135	****PERFORM 2nd MAINTENANCE TASK****		1:00:00	1:00:00		1:00:00
136						
137						
138	2nd WORKSITE TEARDOWN			0:07:57		
139						
140	EV1 egress PWP PFR		0:00:09		F & W avg	0:00:09
141	Attach ORU/PWP to transfer device		0:00:45		F & W avg	0:00:45
142	Transfer ORU/PWP back to CETA	Clear path from worksite to CETA	0:01:50		W avg	0:01:50
143	Translate to CETA	Translation along truss is allowed	0:01:00		Engr. est	0:01:00
144	Attach ORU to CETA		0:01:30		F & W avg	0:01:30
145	Release ORU from PWP		0:00:45		Engr. est	0:00:45
146	Attach PWP to CETA		0:01:30		F & W avg	0:01:30
147	Ingress PFR		0:00:28		F & W avg	0:00:28
148						
149	Translate to 3rd worksite			0:01:28		
150						
151	Release CETA brake		0:00:10		Engr. est	0:00:10
152	Translate to 2nd maintenance worksite	Inboard of alpha joint	0:01:00		Engr. est	0:01:00
153	Set CETA brake		0:00:10		Engr. est	0:00:10
154	Egress PFR		0:00:09		F & W avg	0:00:09
155						
156	3rd WORKSITE SETUP			0:14:27		
157						
158	Attach ORU to transfer device		0:00:45		F & W avg	0:00:45
159	Release ORU from CETA		0:00:30		Engr. est	0:00:30
160	Release PWP PFR from CETA	Includes tether time	0:03:16		F & W avg	0:03:16
161	Tranfer ORU & PWP to worksite		0:01:50		W avg	0:01:50
162	Translate to pallet	Translation along truss is allowed	0:01:00		Engr. est	0:01:00
163	Install PWP PFR in socket	Socket available at worksite	0:03:22		F & W avg	0:03:22
164	Release PWP from transfer device		0:00:00		W avg	0:00:00
165	Tether ORU to PWP	Crew can carry foot restraint &	0:03:16		F & W avg	0:03:16
166	Release ORU from transfer device		0:00:00		W avg	0:00:00
167	Ingress PWP		0:00:28		F & W avg	0:00:28
168						

	A	B	C	D	E	P
169	****PERFORM 3rd MAINTENANCE TASK****		1:00:00	1:00:00		1:00:00
170						
171						
172	WORKSITE TEARDOWN			0:08:25		
173						
174	EV1 egress PWP PFR		0:00:09		F & W avg	0:00:09
175	Attach ORU/PWP to transfer device		0:00:45		F & W avg	0:00:45
176	Transfer ORU back to CETA	Clear path from worksite to CETA	0:01:50		W avg	0:01:50
177	Translate to CETA	Translation along truss is allowed	0:01:00		Engr. est	0:01:00
178	Attach ORU to CETA		0:01:30		F & W avg	0:01:30
179	Release ORU from PWP		0:00:45		Engr. est	0:00:45
180	Attach PWP to CETA		0:01:30		F & W avg	0:01:30
181	Release PWP from transfer device		0:00:28		W avg	0:00:28
182	Ingress PFR		0:00:28		F & W avg	0:00:28
183						
184	TRANSLATE TO ULC			0:03:29		
185						
186	Rotate CETA for starboard translation		0:02:00		Engr. est	0:02:00
187	Release CETA brake		0:00:10		Engr. est	0:00:10
188	Translate to ULC		0:01:00		Engr. est	0:01:00
189	Set CETA brake		0:00:10		Engr. est	0:00:10
190	Egress PFR		0:00:09		F & W avg	0:00:09
191						
192	STOW ORUs			0:25:24		
193						
194	Ingress ULC foot restraint		0:00:28		F & W avg	0:00:28
195	Open ULC	CETA provides adequate access to UPLC	0:01:02		F avg	0:01:02
196	Rotate to CETA		0:00:30		Engr. est	0:00:30
197	Tether to ORU		0:00:29		F & W avg	0:00:29
198	Release ORU from CETA		0:00:30		Engr. est	0:00:30
199	Rotate to ULC		0:00:30		Engr. est	0:00:30
200	Insert ORU in stowage slot		0:01:00		Engr. est	0:01:00
201	Latch ORU to ULC		0:01:00		Engr. est	0:01:00
202	Release tether		0:00:21		F & W avg	0:00:21
203	Close ULC		0:01:02			0:01:02
204	Egress ULC foot restraint		0:00:09		F & W avg	0:00:09
205	Ingress CETA PFR		0:00:28		F & W avg	0:00:28
206	Release CETA brake		0:00:10		Engr. est	0:00:10
207	Translate to 2nd ORU stowage location	Translation along truss is allowed	0:01:00		Engr. est	0:01:00
208	Set CETA brake		0:00:10		Engr. est	0:00:10
209	Egress PFR		0:00:09		F & W avg	0:00:09
210	Ingress ULC foot restraint		0:00:28		F & W avg	0:00:28
211	Open ULC	CETA provides adequate access to UPLC	0:01:02		F avg	0:01:02
212	Rotate to CETA		0:00:30		Engr. est	0:00:30
213	Tether to ORU		0:00:28		F & W avg	0:00:28
214	Release ORU from CETA		0:00:30		Engr. est	0:00:30
215	Rotate to ULC		0:00:30		Engr. est	0:00:30
216	Insert ORU in stowage slot		0:01:00		Engr. est	0:01:00
217	Latch ORU to ULC		0:01:00		Engr. est	0:01:00
218	Release tether		0:00:21		F & W avg	0:00:21
219	Close ULC		0:01:02			0:01:02
220	Egress ULC foot restraint		0:00:09		F & W avg	0:00:09
221	Ingress CETA PFR		0:00:28		F & W avg	0:00:28
222	Release CETA brake		0:00:10		Engr. est	0:00:10
223	Translate to 3rd ORU stowage location	Translation along truss is allowed	0:01:00		Engr. est	0:01:00
224	Set CETA brake		0:00:10		Engr. est	0:00:10

	A	B	C	D	E	P
225	Egress PFR		0:00:09		F & W avg	0:00:09
226	Ingress ULC foot restraint		0:00:28		F & W avg	0:00:28
227	Open ULC	CETA provides adequate access to UPLC	0:01:02		F avg	0:01:02
228	Rotate to CETA		0:00:30			0:00:30
229	Tether to ORU		0:00:29		F & W avg	0:00:29
230	Release ORU from CETA		0:00:30		Engr. est	0:00:30
231	Rotate to ULC		0:00:30			0:00:30
232	Insert ORU in stowage slot		0:01:00		Engr. est	0:01:00
233	Latch ORU to ULC		0:01:00			0:01:00
234	Release tether		0:00:21		F & W avg	0:00:21
235	Close ULC		0:01:02			0:01:02
236	Egress ULC foot restraint		0:00:09		F & W avg	0:00:09
237	Ingress CETA PFR		0:00:28		F & W avg	0:00:28
238						
239	**TRANSLATE TO AIRLOCK**			0:00:39		
240						
241	Release CETA brake		0:00:10		Engr. est	0:00:10
242	Translate to airlock		0:00:10		Engr. est	0:00:10
243	Set CETA brake		0:00:10		Engr. est	0:00:10
244	Egress PFR		0:00:09		F & W avg	0:00:09
245						
246	**STOW TOOLS**			0:06:38		
247						
248	Open toolbox	PFRs already there or not necessary	0:01:02		F avg	0:01:02
249	Release tool from MWS		0:00:26		F & W avg	0:00:26
250	Replace power tool in toolbox		0:00:20		Engr. est	0:00:20
251	Release MWS retractable tether		0:00:21		F & W avg	0:00:21
252	Tether to MWS		0:00:29		F & W avg	0:00:29
253	Release MWS from EMU		0:00:18		W avg	0:00:18
254	Replace MWS in toolbox		0:01:15		W avg	0:01:15
255	Release tether		0:00:21		F & W avg	0:00:21
256	Close toolbox door		0:02:07		F avg	0:02:07
257						
258		Crewmembers cease parallel operations				
259	**AIRLOCK INGRESS**			0:09:24		
260						
261						
262	Translate to airlock hatch		0:01:00		Engr. est	0:01:00
263	Lock safety tether reels		0:00:10		Engr. est	0:00:10
264	Replace safety tethers in pouches		0:01:00		Engr. est	0:01:00
265	EV2 enter airlock		0:06:11		F avg	0:06:11
266	EV2 secure left waist tether to airlock		0:00:00		F avg	0:00:00
267	EV1 unhook EV2s R waist tether & attach to EV1 R tether		0:00:00		F avg	0:00:00
268	EV1 unhook left waist tether		0:00:00		F avg	0:00:00
269	EV1 enter airlock		0:00:00		F avg	0:00:00
270	Close EVA hatch		0:01:03		F avg	0:01:03
271						
272	Total Time Including 1 Hour Task		5:34:40	5:34:40		

Space Station Freedom External Maintenance Task Team Study and Recommendations for Box Type ORUs

Appendix G

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July 1990

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Abstract

The initial phase of the External Maintenance Task Team (EMTT) study at the NASA/ Johnson Space Center (JSC) began with the identification of all external orbital replacement units (ORUs). Each ORU was categorized as Box Type, Mechanical, Electro-Mechanical, or Passive Structure. The Box Type was selected for additional study because concept designs and mock-ups have been produced by most of the work packages. Furthermore, Box Type ORUs have the greatest design maturity of all identified concepts developed because Box Type ORUs can be applied to other ORU types as those designs evolve. Preliminary analysis indicates that these ORUs must be serviced by either an Extravehicular Activity (EVA) crew member or a robotic system. ORUs were evaluated for commonality, EVA/Extravehicular Robotic (EVR) compatibility, and ease of exchange.

The development by all Work Packages and International Partners of a standard Box Type ORU exchange system, which is both EVA and EVR compatible and incorporates standard interfaces, would be a significant step toward the reduction of external maintenance time. A study was initiated by the NASA EMTT to define a standard Box Type ORU exchange system. In the latter phase of the study, a splinter group consisting of personnel from the work packages and the international partners was organized to formulate strawman design standards for Box Type ORUs. EVA tests were performed simulating 0-g in the JSC Weightless Environmental Test Facility (WETF) and 1-g robotic tests at JSC and Ocean Systems Engineering (OSE). Test results and recommendations are outlined in the body of this appendix.

Introduction

The EMTT estimates of external maintenance time requirements for Space Station Freedom (SSF) exceed the baseline EVA time allocation. Reduction of EVA time is being pursued in a number of different areas including the increased utilization of Space Station robotic systems (EVR). The EMTT determined that EVA/EVR commonality will improve Space Station maintenance task performance.

Although high level robotic design requirements and some general design considerations (i.e., ORUs, fasteners, tools/end effectors, and worksite layout) have been generated through the Robotic Systems Integration Standards (RSIS), it is not yet baselined for the SSF Program. Furthermore, at this time RSIS has limited specific robotic hardware interface design standards for ORU designers to work to or choose from. In the absence of NASA imposed ORU hardware standards, each Work Package has developed unique ORU design solutions, most of which are neither common with one another, with EVA/EVR requirements and robotic systems' capabilities. For these reasons, the EMTT initiated a Space-Station-wide program intended to generate consensus ORU design standards and to build hardware to test these concepts. All information collected on ORUs by the EMTT from the work packages and international partners was incorporated into the Fisher-Price ORU Database.

This segment of the program focused on developing strawman standards and requirements for the Box Type ORUs. The three other categories of ORUs (Electro-Mechanical, Mechanical, and Structural) will be addressed at a later time.

The objectives of this program are to provide recommendations for Box Type ORU standards and commonality. These standards would include common interfaces for both EVA and EVR, visual cues and status indicators, clearances for insertion and removal of the ORU, common insertion/removal kinematics, docking requirements, tools, and tool interfaces.

Statement of Problem

The NASA EMTT has identified over 5000 external ORUs, of which more than 650 have been classified as Box-Type. Most of the Box Type ORUs are avionics or electrical, but some contain fluid components. Serviceability and maintainability of Space Station ORUs are addressed in two program documents: Man Systems Integration Standards (MSIS, NASA-STD-3000) and Robotic Systems Integration Standards (RSIS, NASA-STD-TBD). Both are high-level requirements documents that do not necessarily drive common design solutions. This has led to wide variations in design of similar components by the Work Packages and International Partners. This non-standard approach has led to complex servicing tasks, excessive logistics, tooling, and crew training requirements. There is no common method of exchanging Box Type ORUs by either the EVA/EVR. No known organization has been tasked with nor given the authority for a coordinated development of SSF specific hardware ORU standards.

Examples of Box-Type ORUs are presented below (Figure G-1) to illustrate the significant differences in design. These differences will result in non-standard tooling requirements,

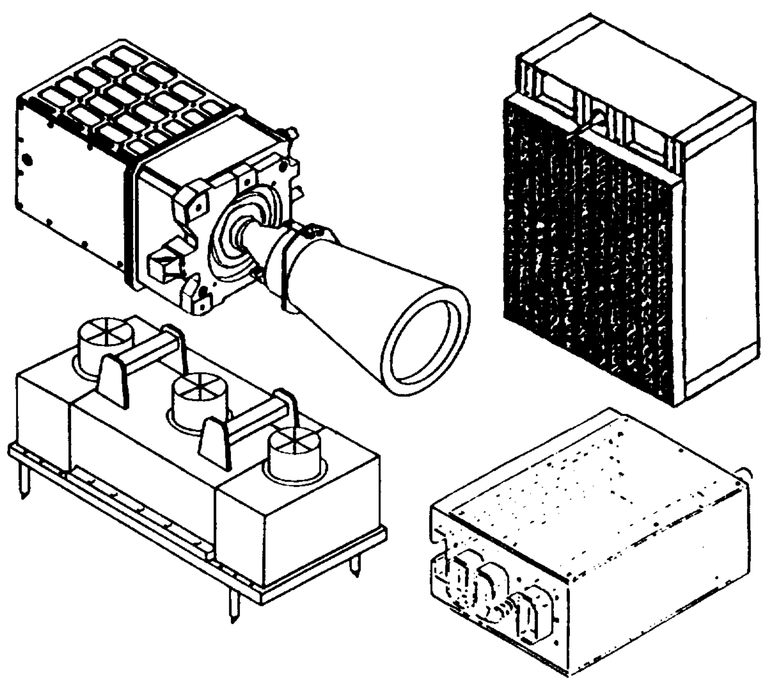

Figure G-1. Typical Box Type ORUs

unique installation/removal procedures, increased crew training, and unique logistics requirements, all of which compound to adversely affect external maintenance complexity and time.

Approach

Utilizing the Fisher-Price ORU Database created by the EMTT, Box Type ORUs were divided into size groups for more detailed study and analysis. A typical ORU handling cycle is shown in Figure G-2. A review of the removal and replacement portion of the cycle was conducted to better understand the requirements imposed on this group of ORUs. The overall requirement types are illustrated in Figure G-3.

An ORU splinter group was formed, with representatives from the work packages and international partners attending the mid-term EMTT review held April 17 through 19, 1990 at JSC. The purpose of this group was to establish strawman standards for Box Type ORUs. A preliminary design concept for Box Type ORUs that is EVA/EVR compatible was developed and presented at the EMTT mid-term meeting.

Following the mid-term review, a preliminary version of the strawman design standard was compiled and reviewed with the participants.

A representative Box Type ORU mock-up (Figure G-4) incorporating the strawman standards was fabricated for evaluation in the JSC WETF, the OSE Robotics Testing and Integration Laboratory (RTAIL) and the JSC Robotic Systems Evaluation Laboratory (RSEL). Time constraints precluded incorporation of blind mate fluid and electrical con-

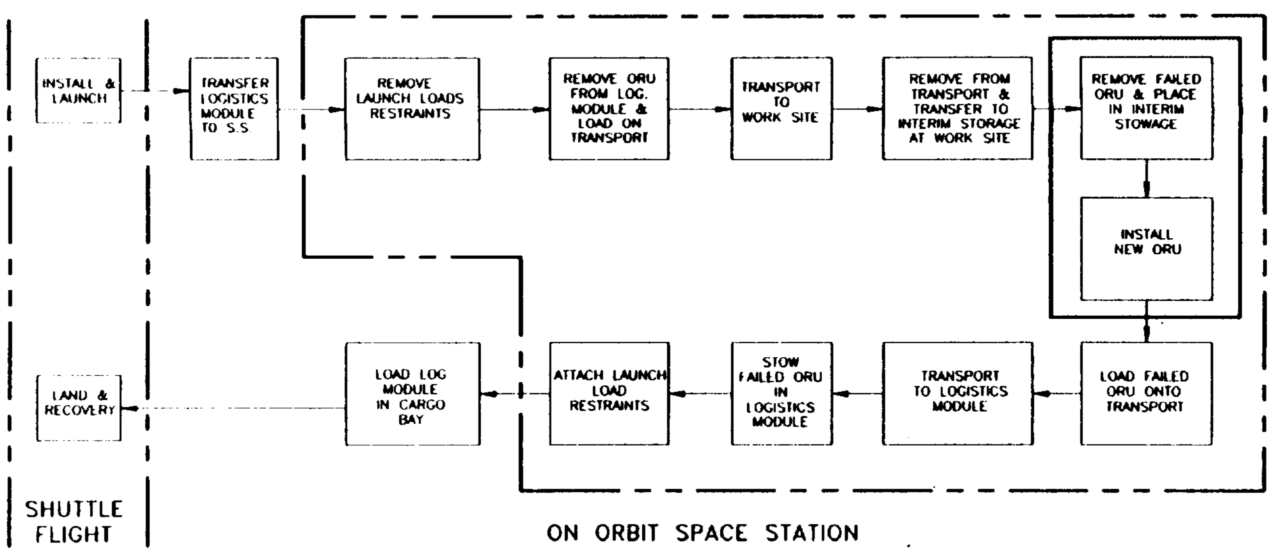

Figure G-2. ORU Handling Cycle

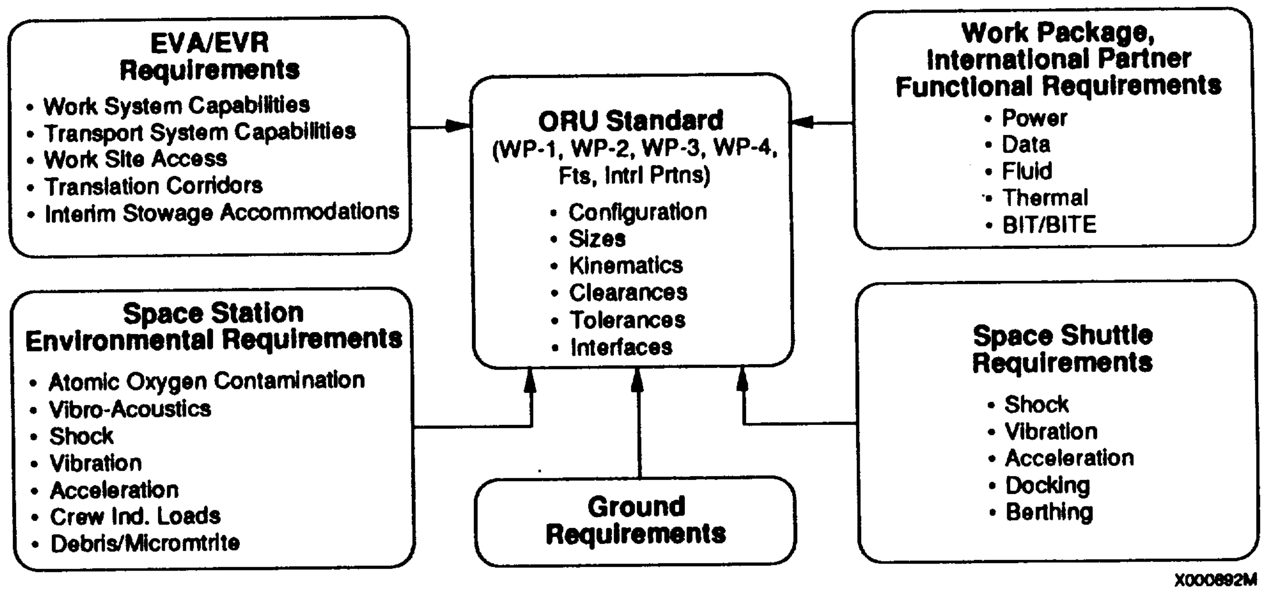

Figure G-3. Overall Requirement Types

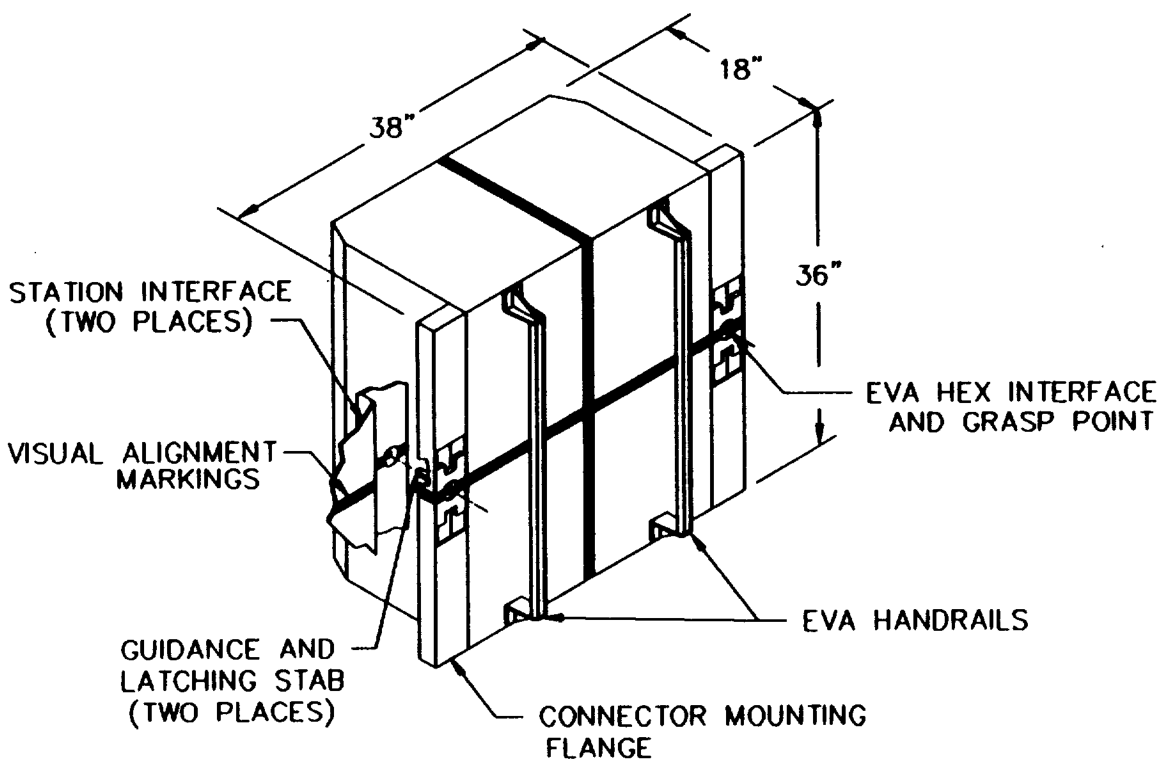

Figure G-4. Representative ORU Mock-up

nectors and thermal interfaces into the mock-up. The purpose of these tests was to evaluate consensus strawman design standards from the perspective of EVA/EVR servicing.

Assessments of a strawman design standard were made and recommendations for an ORU exchange system developed.

Results and Discussion

The results of the EMTT Box Type ORU Study can be broadly divided into the following areas:

- Strawman consensus design standard
- Box Type ORU fabrication
- Testing and evaluation of the Box Type ORU
- Preliminary design of a multi-purpose torque tool

These standards were applied to the fabrication of a mock-up Box Type ORU (Figure G-4) and the preliminary design of a multi-purpose torque tool (MPTT). WETF testing with suited astronauts, and one-g testing with both a telerobotic system and automated robotic system, was done to evaluate the strawman standards within the limited time and resources available.

Strawman Standards Development

At the mid-term review, the ORU Splinter Group developed and prioritized candidate features to be incorporated into the ORU design standard. This rating was established to denote the importance of standardization for each item identified. This list, with the assigned ratings, is presented in Table I. Each of the high priority (3) ratings were discussed in depth, and tentative agreements were reached on means of meeting the requirement. The highest priority candidates were then combined to form the consensus strawman standard shown in Table II.

TABLE I

Candidate Features for Box Type ORU Design Standards

Priority Ranking (for Standardization) (0 - Low, 3-High)

1.	Fastener type		3
2.	Clearance around a fastener		3
3.	Bolt head size		3
4.	Interfaces	a) Tool to ORU	3
		b) ORU to station	3
5.	Kinematic motion		3
6.	Alignment guides		3
		a) Tool to ORU	3
		b) ORU to station	3
7.	Visual cues		3
8.	Box sizes and style		1
9.	Use of Metric or English units		3
10.	Thermal interfaces		3
11.	Connectors (electrical & fluid)		3
12.	Status indicators		3

13. Tools 2
14. Soft dock 3
15. Identification & Warning labels 2
16. Thermal coverings 1
17. Keep alive power 1
18. Surface finish 0
19. Verification testing 0

TABLE II
Consensus Design Standards for Box Type ORUs

The purpose of this strawman standard is to provide a guide to be expanded, confirmed, and implemented as a NASA SSF standard for Box Type ORUs. All standards will be verified through further engineering analysis and testing.

I. Fastener types - Captive ACME thread with locking feature as required.

II. Clearance around fastener head

A. The final design requirement will place all fastener heads at the same height above the box. The range being considered is +/- 1 in. from the surface.

B. Side clearance will conform to MSIS and NASA Standard 3000 Section 14.3.2.5 (c) which states:

1. When only tool access is required, a 2.5 cm (1.0 in.)minimum clearance around the fastener head or drive stud for insertion, actuation, and removal of the drive end of the tool.

2. A minimum of 7.6 cm (3.0 in.) should be provided for clearance between a tool handle engaged on a fastener or drive stud and the nearest piece of hardware. The tool handle should be able to maintain this clearance through a full 180-degree sweep envelope.

(These specifications are illustrated in Figure G-5)

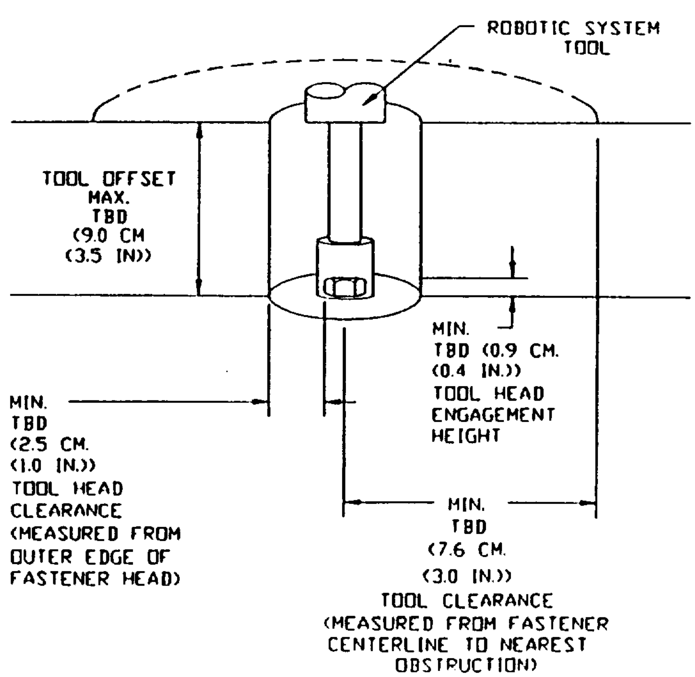

Figure G-5. Fastener Clearance Envelope

III. Fastener head size - 11 mm double height EVA Hex Head as defined in the EVA Tool Catalog.

IV. Interfaces

   A. Tool to ORU

      1. All must accept the same tool, have tool hard dock, torque reaction capability, and tool alignment.
      2. Handling points will add handling capability and a visual indication that it is a handling point.
      3. The attachment mounting will be flush with the surface of the ORU.
      4. Fastener head shall be mounted at top and located on flange to side of box (see Figure I-8)

   B. ORU to station

      1. A soft dock capability shall be incorporated in the fastening mechanism.
      2. Station mounting hardware shall incorporate an adequate alignment guide.

V. Kinematic motion

   A. Tool to ORU

      1. All fastening will be done in a clockwise rotation of the fastener.
      2. Robot & EVA motion for connection will be in one axis.

   B. ORU to station

      Soft dock insertion will be done with single axis translation.

VI. Alignment Guides

   A. Tool to ORU

      +/- 0.5 in. linear alignment guide.

   B. ORU to station

      Determined from graph produced by NASA Goddard Space Flight Center (Figure G-6). Guides must provide alignment envelope from 3/8 in. to 3/4 in., depending on the size of the ORU.

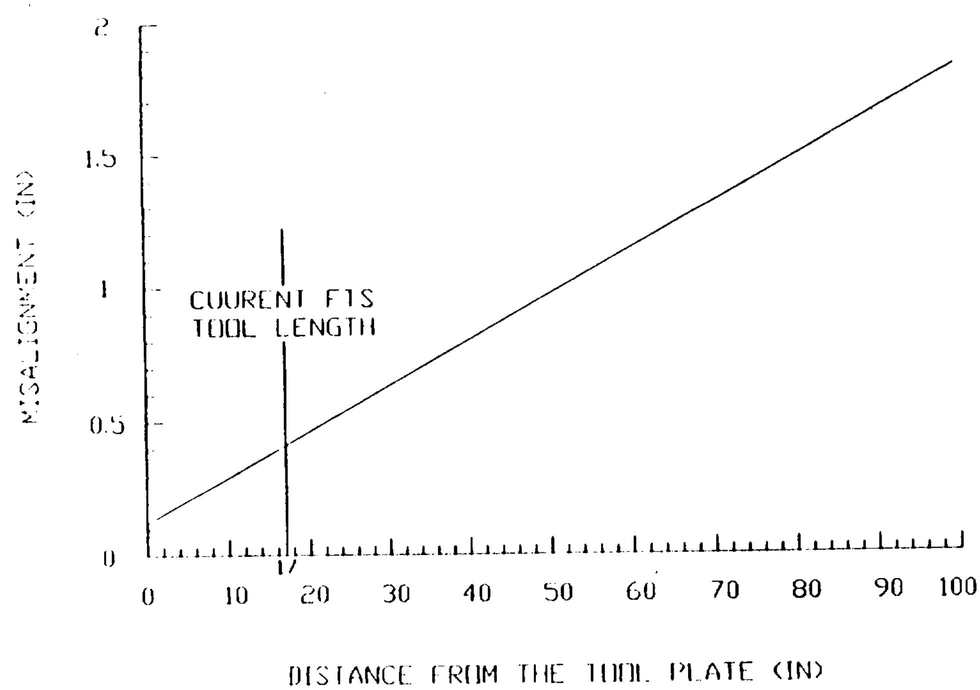

Figure G-6. Box Type ORU Alignment Guide

VII. Visual Cue

A. ORU to station

Two dimensional targeting must be provided.

VIII. Box Sizes

A. Standard Sizes for Box Type ORUs (Figure G-7)

1. Fixed width for various classes.
2. Incremental depth to a maximum depth.
3. Incremental lengths to a maximum, picking up bolts at standard lengths.

B. Standard Types of ORU Mounting (Figure G-8)

1. Top mounted
2. Bottom mounted

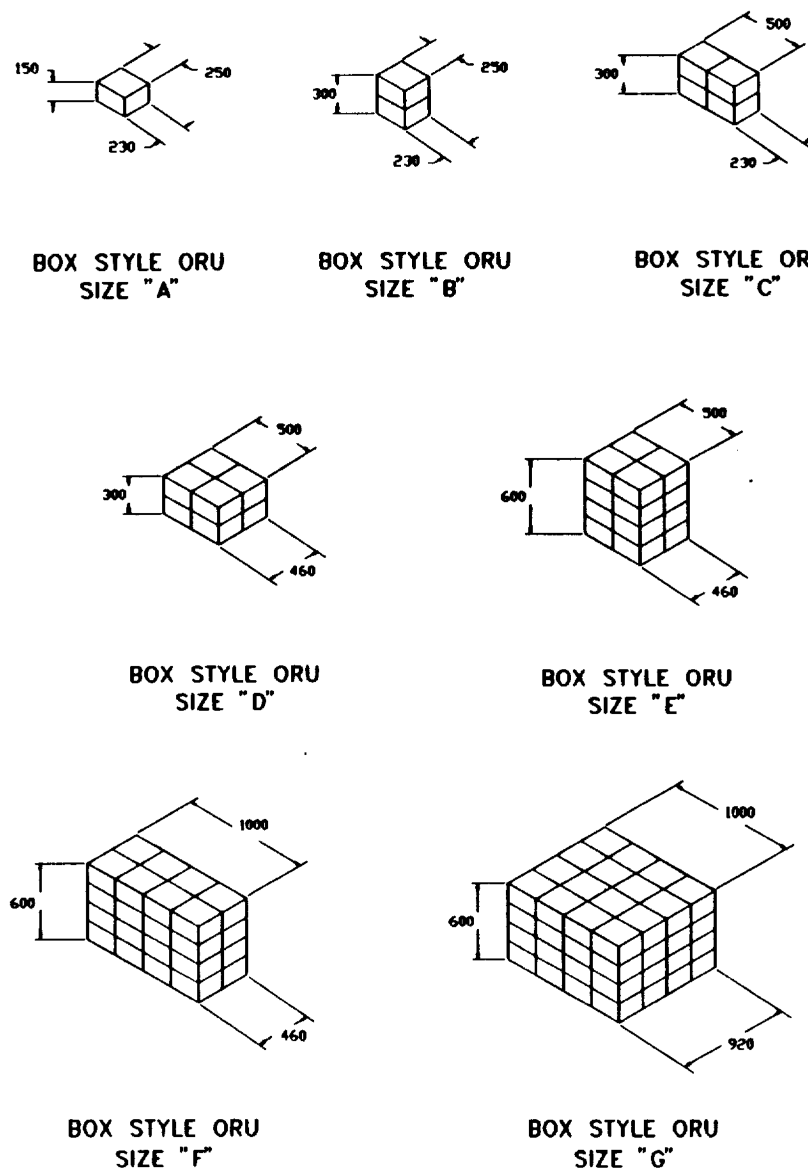

Figure G-7. Standard Sizes for Box Type ORUs

IX. Metric
All ORU external dimensions must be expressed in millimeters.

X. Thermal Controls
A passive thermal interface is preferred, but if engineering development fails to meet the requirements, an active system will be pursued.

XI. Connectors
Removal and installation of ORUs must require mating of blind-mate fluid and electrical connectors only.

XII. Status Indicators
Standard indicator clearly visible to the work system at the work site indicating soft dock and hard dock (electrical and fluid connectors fully seated, cold plates properly installed) for both insertion and removal.

XIII. Tool
- A. All tools must meet the required interface standard.
- B. Tool must be able to develop 50 ft.-lbs (max.) of torque.
- C. In its handling mode, all interfaces shall be two fault tolerant.

XIV. Soft Dock (ORU to Station)
- A. Soft dock is required on all ORUs with a 5 ± 2 lb. insertion and removal force.
- B. The soft-dock mechanism will position ORU for fastener and connector alignment.
- C. The soft-dock operation will be completed prior to the engagement of any connectors or threaded fasteners.

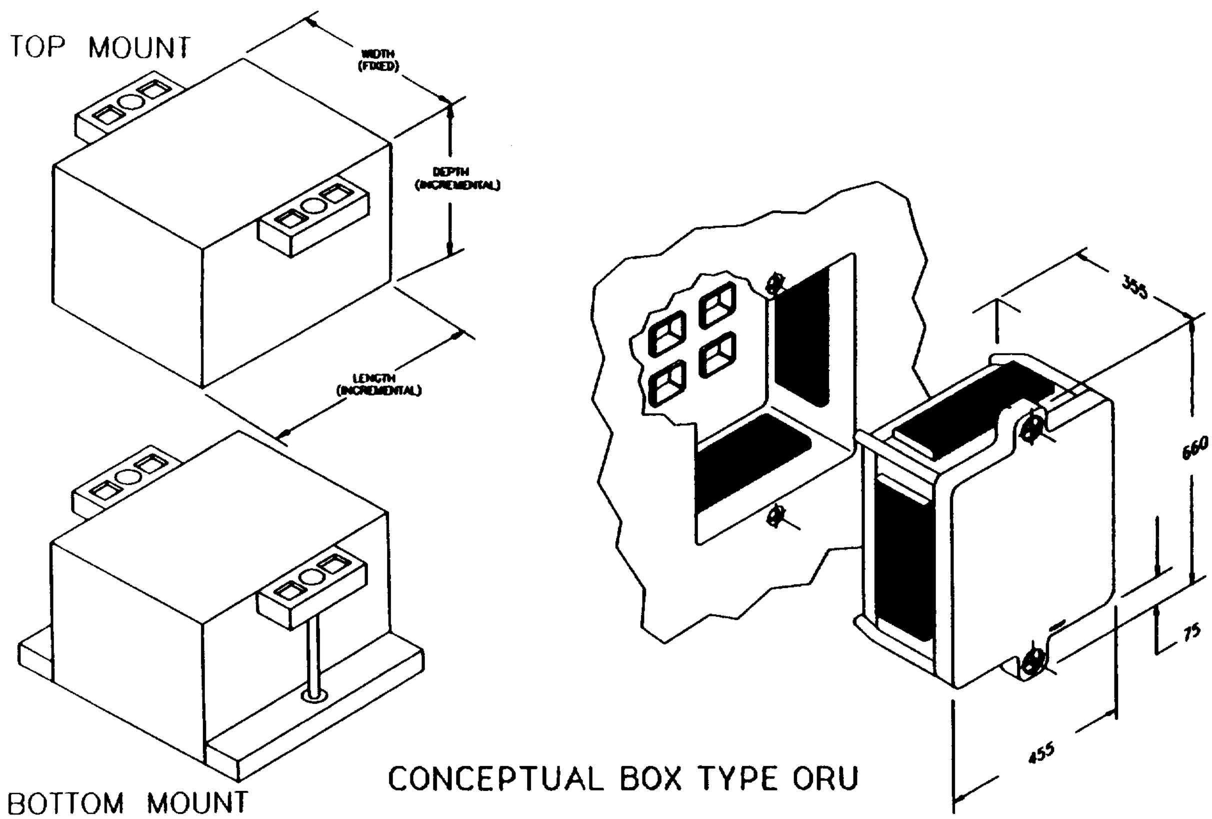

Figure G-8. Standard Box Type ORU Mountings

XV. Identification/Warning Labels
   A. There will be a standard label including the following:
      1. Serial Number
      2. Hazards Identification
      3. Name
   B. ORU location will have corresponding identification label.

XVI. Thermal Covering and Meteoroid Shielding
All coverings will be incorporated into the box design. The standard handling fixture will be operable by the standard ORU tool.

XVII. Electric Grounding
All grounding must not require a separate connect or disconnect operation.

XVIII. Keep Alive Power
   A. All ORUs should survive without keep alive power for 24 hours with no operational degradation.
   B. ORUs that require keep alive power will require a standard interface.

Box Type ORU Mock-Up

The strawman ORU was constructed of light-weight aluminum and cloth mesh materials to facilitate handling in 1-g by the robotic arms and by the EVA crew members in the JSC WETF. This ORU was patterned after the Work Package 4 battery assembly. A simple adaptation of the EVA power tool (Figures G-9 and G-10) permitted use of the "H" handle for torque reaction and ORU handling by the robotic manipulators. The "H" handle was

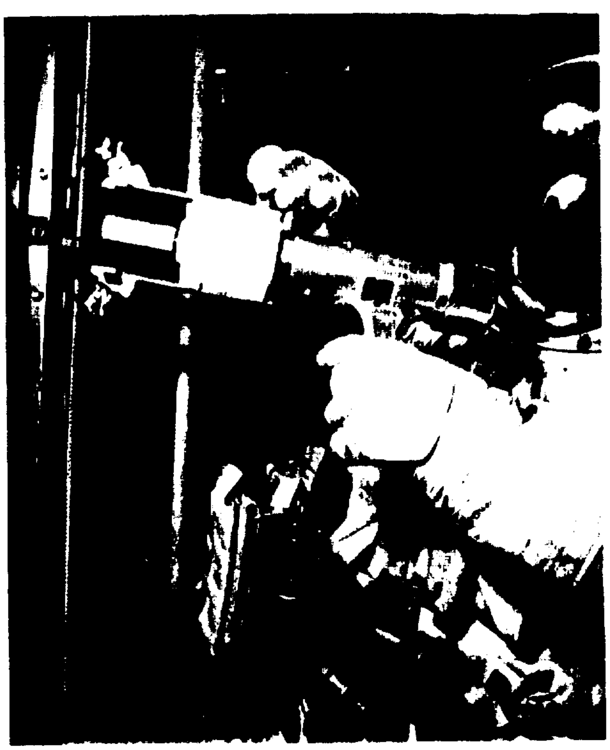

Figure G-9. EVA Tool Modified for Use With "H" Fitting (Pre-installation)

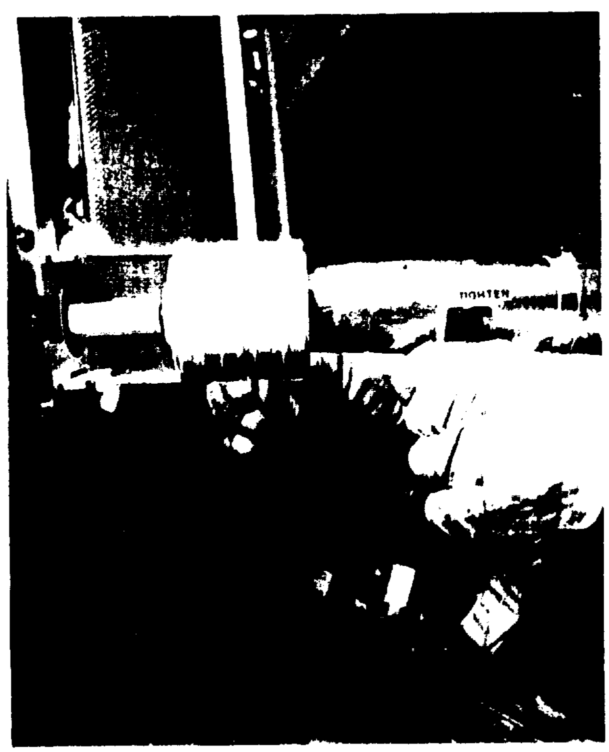

Figure G-10. EVA Tool Modified for Use With "H" Fitting (In place on "H" fitting) selected as a representative interface that met the strawman standards but was not necessarily the recommended design solution.

The "H" fitting is shown in Figure G-12. Centered in the "H" fitting is the hex head of the OSE designed latch bolt. This attachment mechanism incorporates a "soft-dock" feature that requires a minimum of 5 pounds of force to insert or remove the latch bolt from its socket. Figure G-13 is a bottom view of the latch bolt showing the fingers that provide the latch to the socket. Once the latch bolt is inserted into its socket, rotation of the hex head (clockwise) translates the body of the latch bolt behind the fingers providing a positive hard dock and the force necessary for engagement and seating of the electrical and/or fluid connectors. Reversing the rotation of the hex head causes the ORU to be moved away from its seated position de-coupling the electrical and/or fluid connections. The ORU is retained in position by the soft dock feature until removed by either the robot or crew.

The mock-up of a Box Type ORU and a simulated station interface structure is shown in Figure G-11. The physical dimensions of this mock-up were the same as Rocketdyne's Battery Box which is located on the IEA pallet. This battery sub assembly is one of the largest Box Type ORUs that is scheduled for handling by either an EVA crew member or a robotic system. A pallet simulation was constructed to provide an access corridor and interface similar to that planned for the IEA-pallet.

Figure G-11. EMTT Box Type ORU Mounting Structure

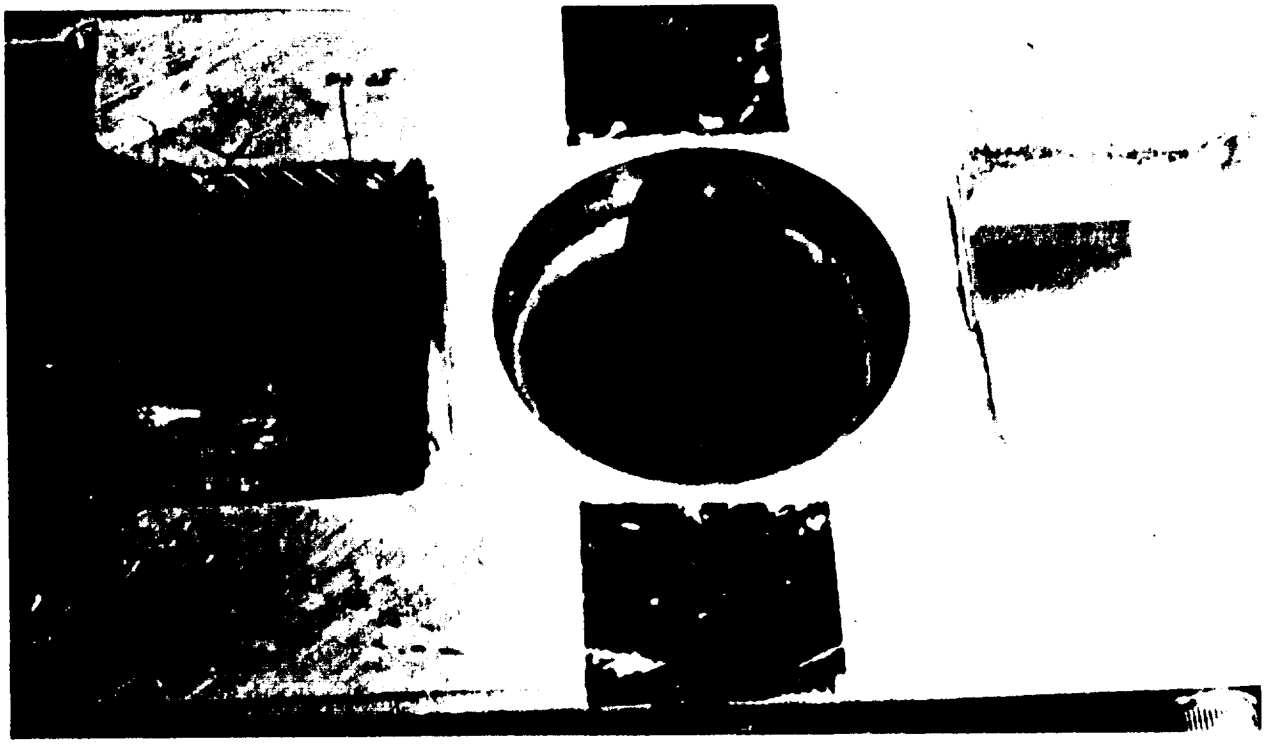

Figure G-12. Top View of Latch Bolt Centered in "H" Fitting

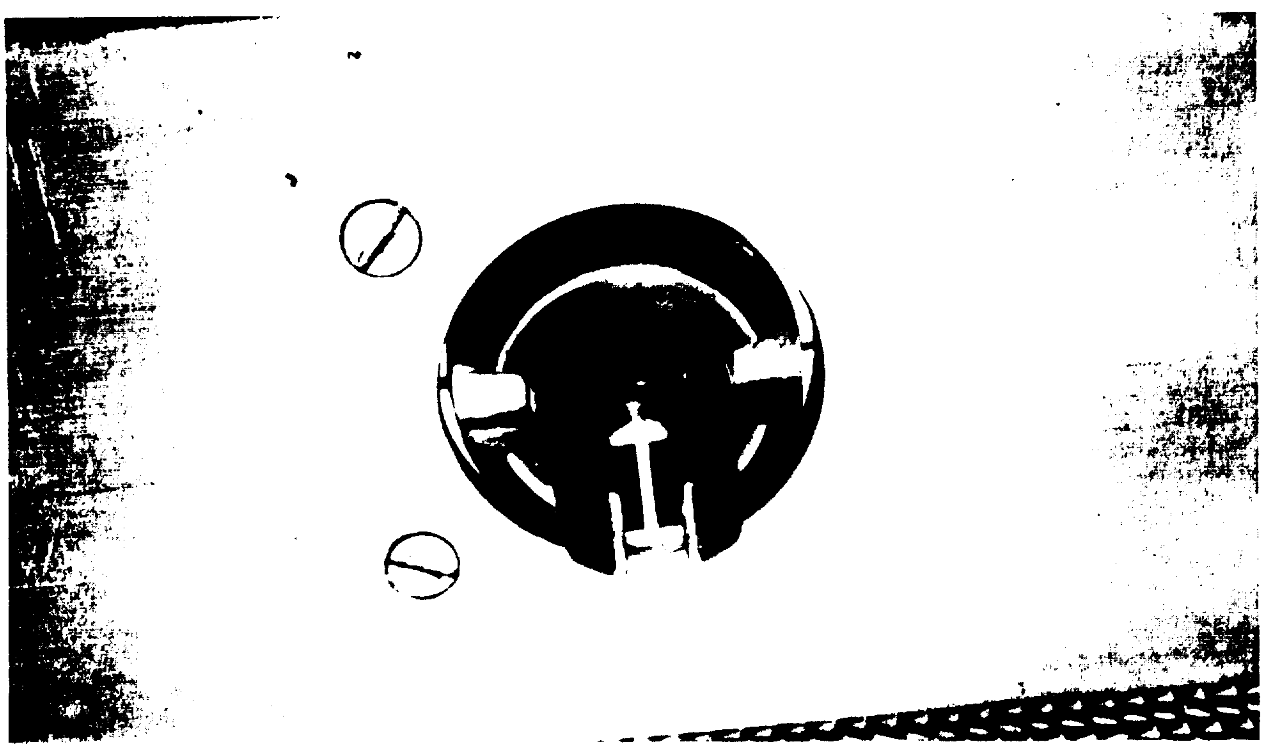

Figure G-13. Bottom View of Latch Bolt Showing Soft Dock/Latching Fingers

EVA Test and Evaluation

The first ORU exchange evaluation tests were conducted in the JSC WETF.

Three teams of two astronauts evaluated the exchange in an end-to-end task simulation. The task began with transporting crew and equipment via the Crew and Equipment Translation Aid (CETA). The ORU and equipment were then transferred from the CETA to the pallet via the clothesline where an ORU exchange was performed. The handling and installation of the ORU are shown in Figures G-14 through G-20. Details of the entire EVA simulation are included in Appendix H4. The ease of handling and attaching this ORU can be seen in these pictures. The WETF tests were designed to obtain EVA overhead task time information and evaluate a strawman "box type" ORU. The removal and installation of the ORU on the pallet was accomplished rapidly and without difficulty. Debriefings of each of the astronaut teams were held after each simulation. A summary of the crew comments follows.

- The visual alignment guides (horizontal and vertical black lines) were adequate for inserting the ORU into the pallet.
- The soft-dock feature of the latch bolt worked well but should incorporate higher spring resistance to provide tactile feedback to the crew members. An indicator that provides a positive indication of both soft dock and hard dock is required.
- Latching the power tool to the ORU is required only if the tool is being used to move the ORU.
- Two tether points should be provided on ORUs near the center of the handrails.

Figure G-14. Retrieving ORU from temporary stowage onstanchion at work site

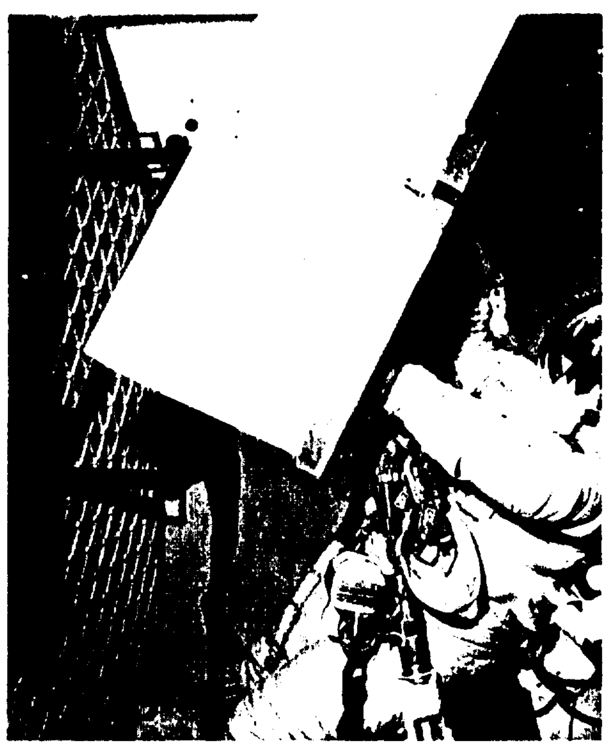

Figure G-15. Maneuvering the ORU into position for installation

Figure G-16. Insertion and Alignment of ORU in Mounting Structure

Figure G-17. Final Manual Positioning of ORU

Figure G-18. Pre-installation of EVA Tool on Hex Fastener and "H" Fitting

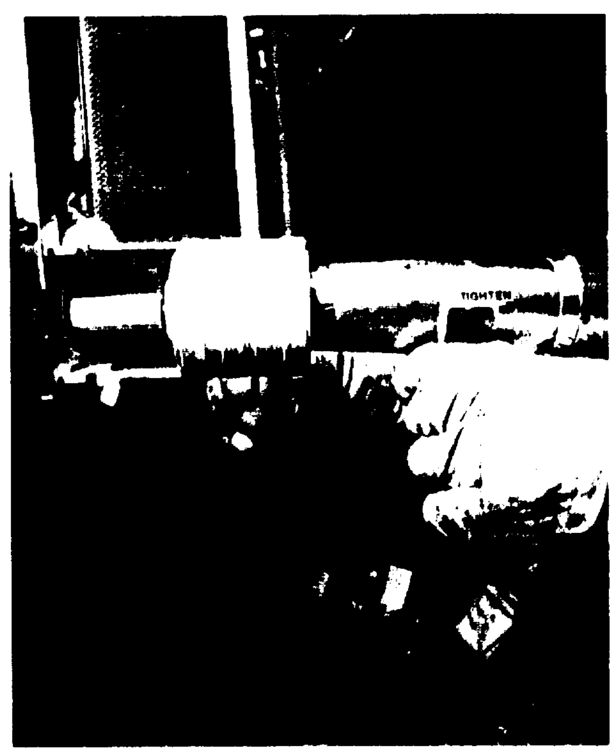

Figure G-19. EVA Tool in "Locked" Position on Left ORU Fastener

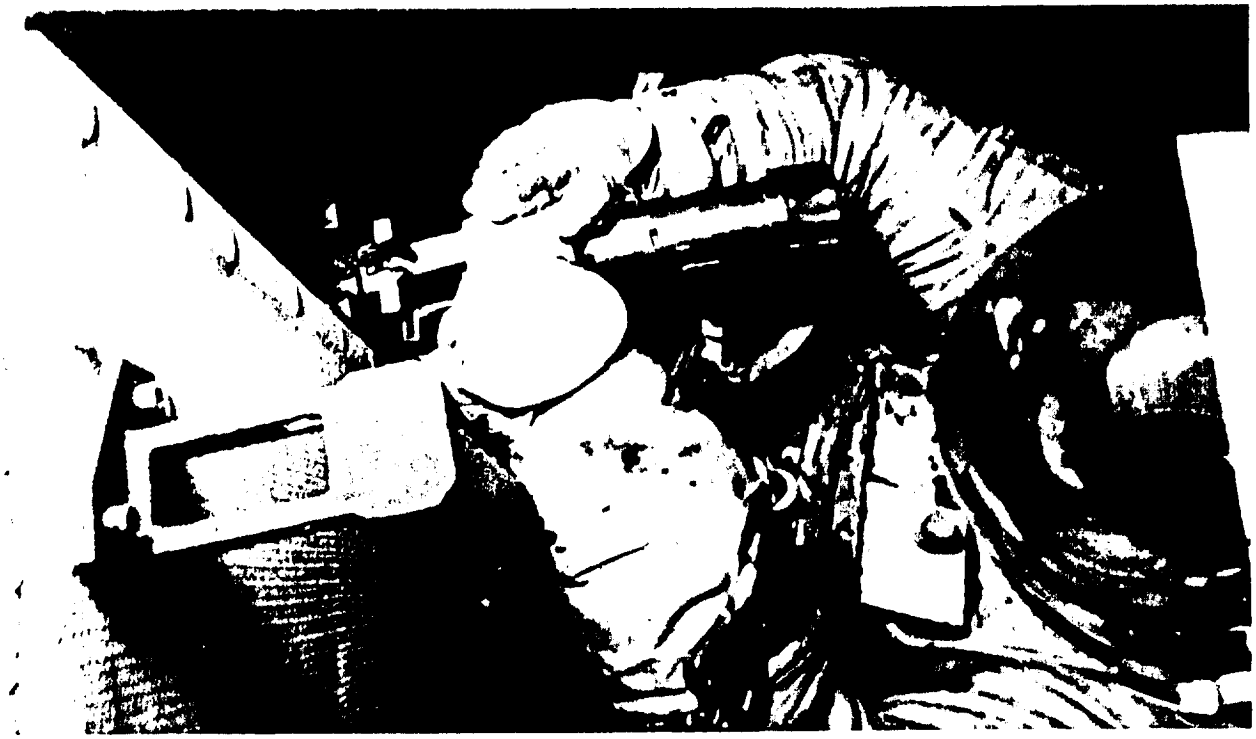

Figure G-20. EVA Tool being installed on Right ORU Fastener

- Incorporate handrails or other suitable means of EVA ORU handling.
- The size of the ORU gave no significant difficulty in handling at the work site. Larger ORUs could present some difficulty in maneuvering and installation.

Robotic Test and Evaluation

The second set of tests evaluated the ORU handling with two different robotic systems: an Oceaneering/GE manipulator arm, and a Robotics Research manipulator arm. The GE manipulator is an anthropomorphic, six degree-of-freedom (DOF) with a parallel jaw end effector and nut driver. Its control system utilizes a spatially correspondent, force reflecting, master/slave configuration. The Robotics Research manipulator is anthropomorphic and seven- degree-of-freedom, with parallel jaw end effectors. It can be operated in either a teleoperated or an automated mode. Both modes used position control (no force-reflection). The teleoperated mode uses two 3-DOF joysticks for the master control; this configuration is similar to the Shuttle Remote Manipulator System (RMS) controllers.

It should be noted that the purpose of these tests was to evaluate the compatibility of the strawman Box Type ORU with robotic systems and not to establish SSF ORU changeout time lines.

The steps followed in simulating the ORU exchange by both the GE and Robotics Research manipulator were:

- start with manipulator arm in the rest position
- move the arm to first latch bolt
- grasp the "H" handle (actuate latch bolt)

- release the "H" handle
- move arm to (second) latch bolt position
- grasp "H" handle (actuate latch bolt)
- remove ORU from mounting structure
- move ORU away from mounting structure
- move ORU to mounting structure
- insert ORU into mounting structure (soft dock)
- release "H" handle
- move arm to central position and lock-out manipulator joints

The box weight was at the limit of both robotic systems' manipulative capabilities for the motions required for this task. The box's weight was counter-balanced with a mass-and-pulley system to facilitate one-g manipulation. This method negated forces in the vertical direction only; coupled forces and torques were encountered when the robotic system moved the mock-up in other axes.

This mock-up was designed for handling by astronauts in the WETF and in one-g by robots. Test conditions could be improved through use of the WETF, an air-bearing floor, or an improved counterbalance system.

Figure G-21. Robot Arm Operator with Master Control

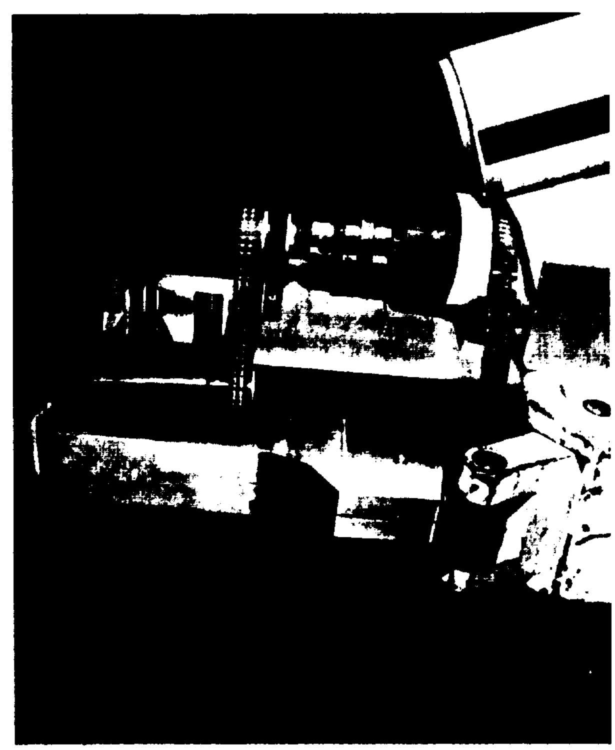

Figure G-22. Wrist-mounted Video Camera

OSE Robotics Testing and Integration Laboratory (RTAIL) Tests

The initial evaluation of robotic handling of the strawman ORU was accomplished in the OSE RTAIL. An Oceaneering/GE hydraulically powered arm employing force reflective feedback in a master/slave configuration was used for this evaluation.

The simulated ORU and mounting structure were configured in the vertical plane similar to that used in the JSC WETF. Figure G-21 shows the operator in position with the master control arm and video. The jaws of the hydraulically powered manipulator, "nut runner" (latch bolt operator), and wrist-mounted video camera are shown in Figure G-22. Figures G-23 and G-24 are ORU, robot arm, and end effector used in these evaluation tests.

The exchange was accomplished with little or no difficulty. An overview video camera proved to be a significant benefit in the insertion of the strawman ORU into the SSF support structure. The wrist-mounted camera was of no use during this portion of the task. The wrist camera was valuable in inserting the manipulator jaws onto the "H" fitting.

An ORU and mounting structure having more rigidity would improve the handling capabilities when performing this type of testing.

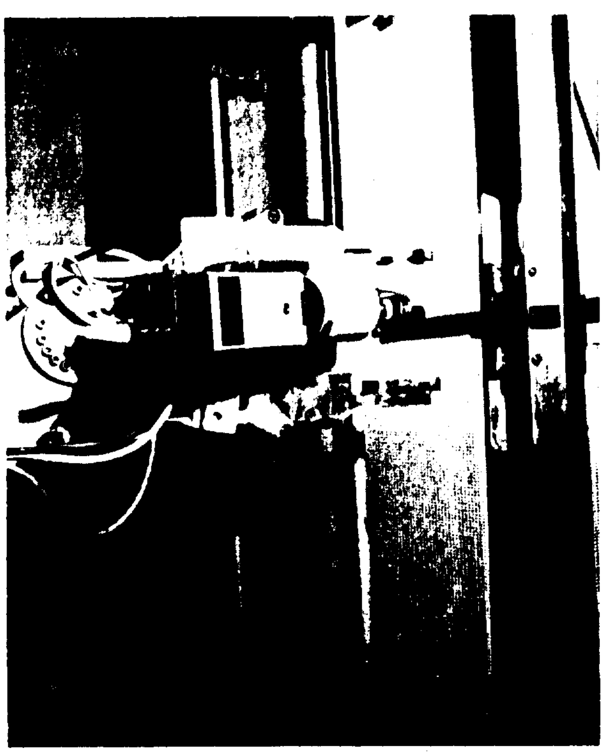

Figure G-23. Robot Arm End Effector

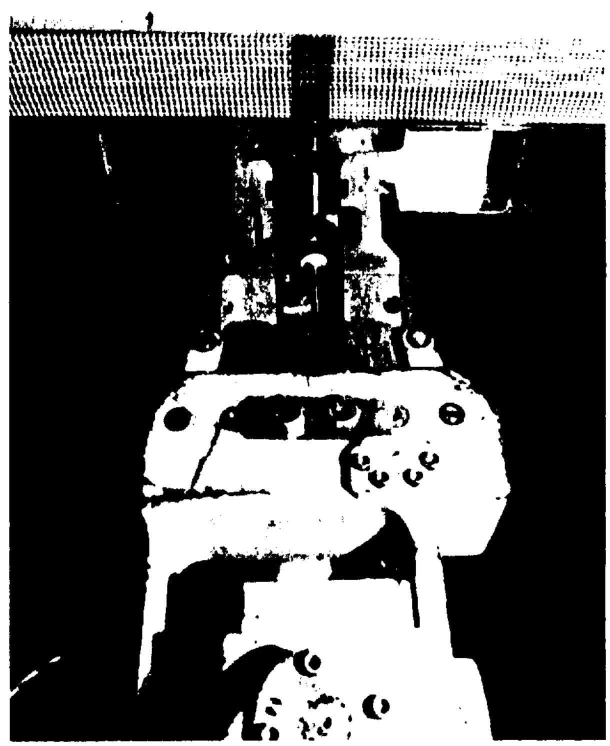

Figure G-24. Robot Arm/End Effector and ORU

JSC Robotics Systems Evaluation Laboratory (RSEL) Testing

The same strawman ORU was used at the RSEL at JSC for evaluation of the ORU exchange using the Robotics Research manipulator. Two ORU exchange procedures were followed. The first was a teleoperated change out much like that performed with the GE force reflecting robot. The second test was performed under full executive control by a host computer. The only human operator input required was the press of a button to initiate the automatic changeout sequence. The purpose of the first test was to verify the results of the earlier teleoperated test performed by the GE robot. The purpose of the second test was to obtain additional data regarding how well the strawman ORU box lent itself to autonomous placement.

The major difficulty encountered while performing this teleoperated task was that of finding good camera locations. Camera locations approximating those of an SSF manipulator were used. A "bird's-eye" camera viewing angle would have simplified the change-out procedure. Automatic change out was accomplished without difficulty. Camera viewing angles did not affect the performance of the task because the operator only needed one camera view to see that the manipulator was performing the task properly.

The ORU box volumetric size was at the upper limit of the robot's capability. A grapple point at the center of the top (exposed) face of the ORU is needed to reduce end effector reaction torques during the soft dock procedure.

The operators position for the Robotics Research system is shown in Figure G-25. An overview of the work site in the JSC RSEL is presented in Figure G-26. The control system and instrumentation are shown in Figure G-27. Figures G-28 through G-31 cover the steps of ORU exchange beginning with acquiring the ORU at the "H" fitting to removal of the ORU from the mounting structure.

Multi-Purpose Torque Tools

The Multi-Purpose Torque Tool (MPTT) was conceived and a preliminary design initiated (Figure G-32). This tool incorporates the following features:

- Insertion misalignment of up to 30 degrees
- Soft Dock
- Hard Dock
- Eleven-millimeter hex head fastener drive
- Torque reaction integral with the tool/ORU
- Turns Counter
- Tightening and loosening up to 50 ft-lbs
- Handles for EVA operation
- EVR interface
- Indicators for hard latch and direction of rotation

The tool depicted in Figure I-32 is configured for EVA WETF operation. A minimum of modification is required to the external configuration when designing for EVR use.

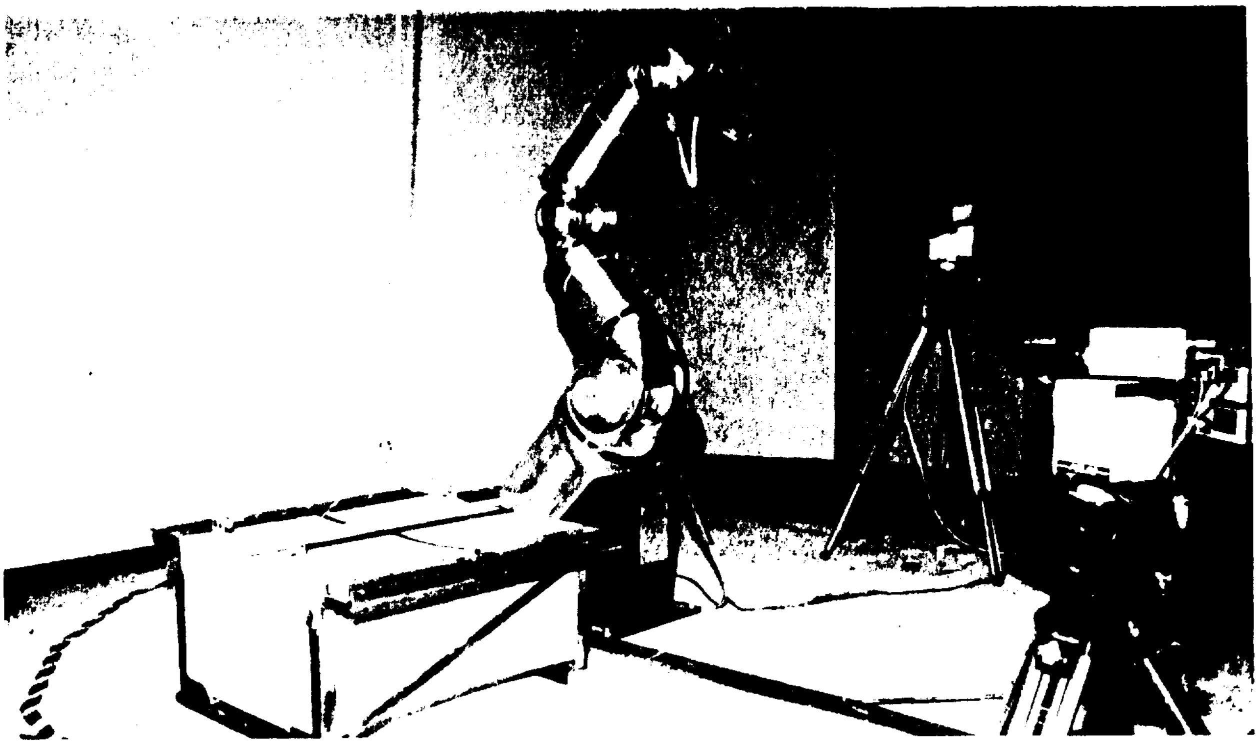

Figure G-25. Operator's Position for Robotics Research System

Figure G-26. Overview of the JSC RSEL work site

Figure G-27. JSC RSEL control system and instrumentation

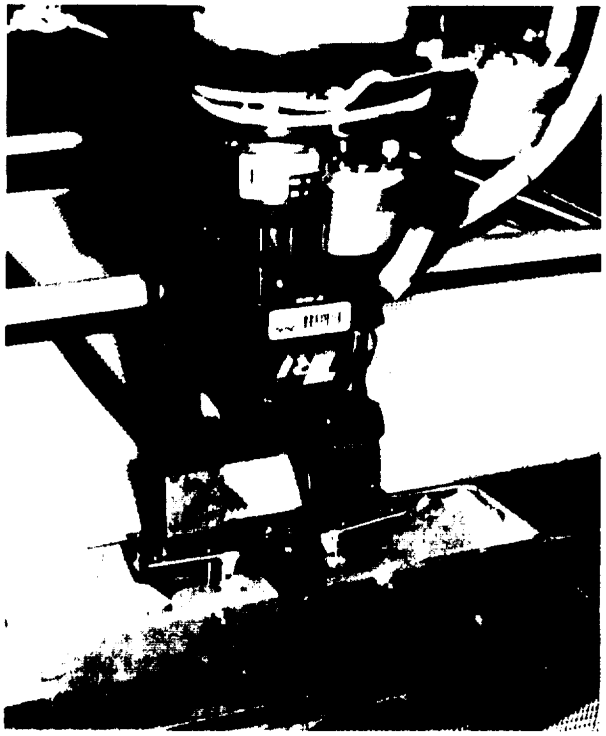

Figure G-28. Robot End Effector acquiring ORU

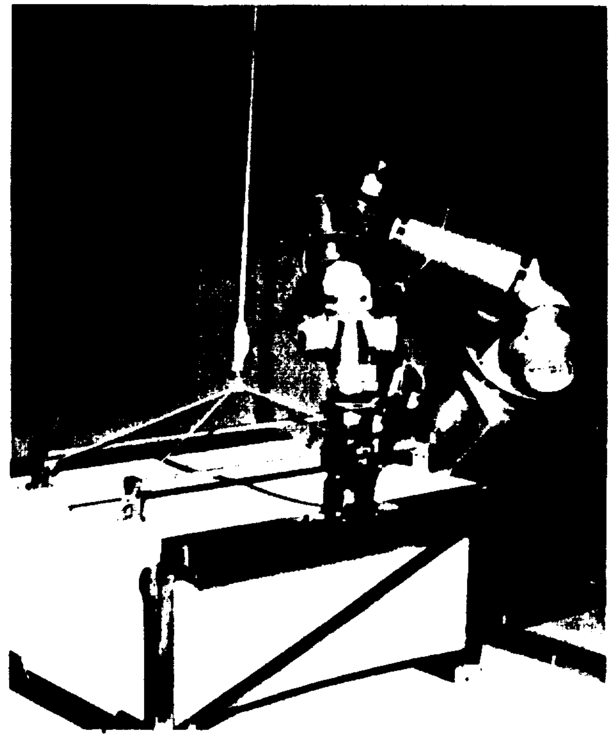

Figure G-29. ORU Fastener being loosened by nut runner

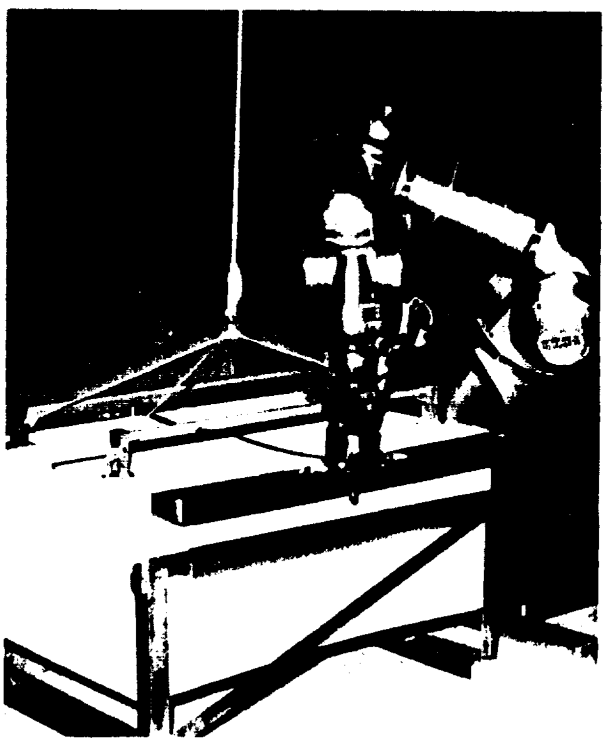

Figure G-30. ORU being removed from mounting structure

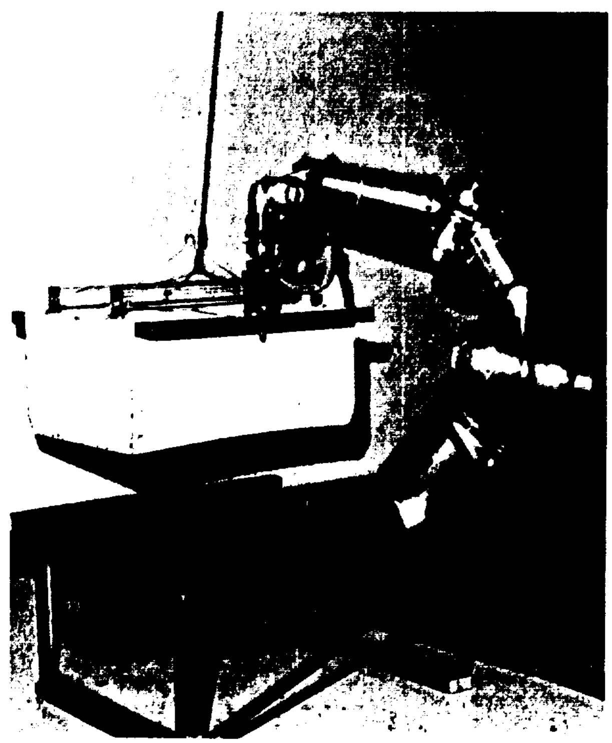

Figure G-31. ORU removed from mounting structure

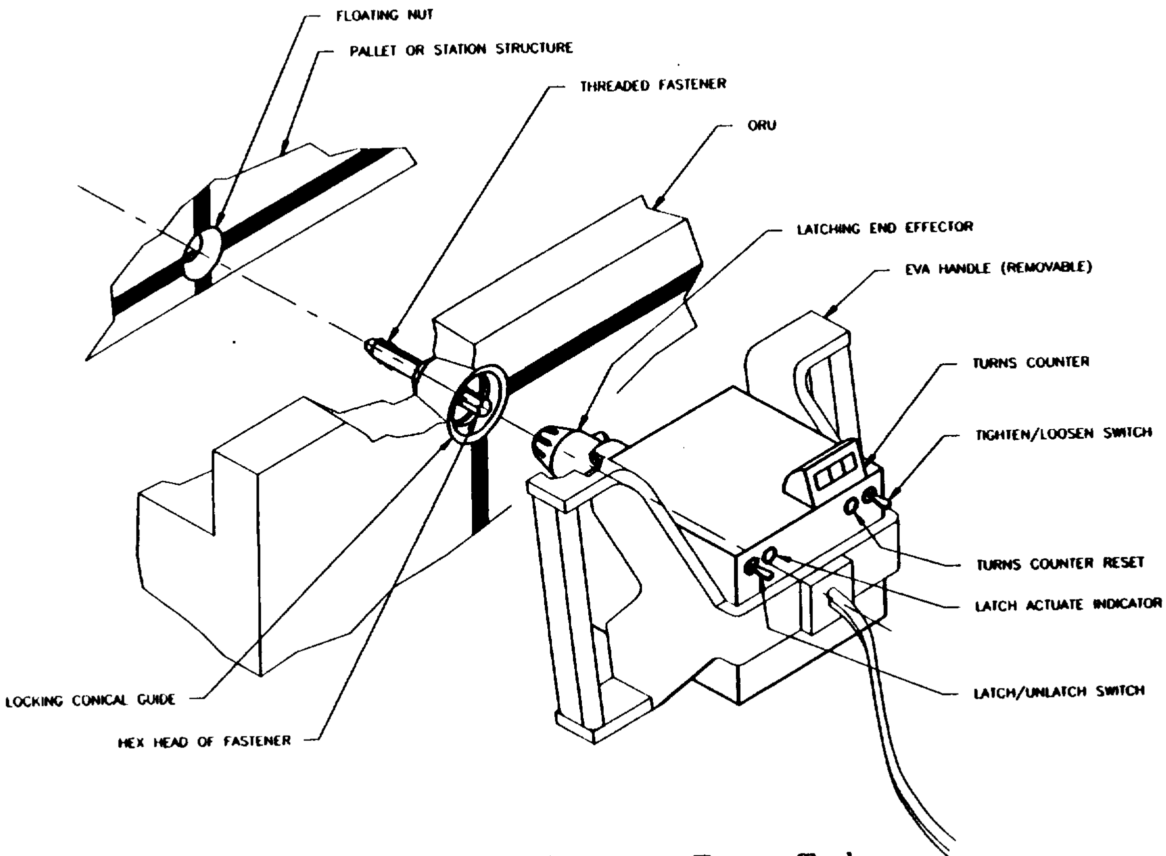

Figure G-32. Multipurpose Torque Tool

Summary

These tests identified the need for a systems approach to the design of both the ORU and the robotic system, as well as the astronaut capabilities. Camera positions and orientation coverage are critical to robotics task performance. Tests in both JSC's RSEL and OSE's RTAIL required a counterbalance system to handle the weight of the strawman ORU in the one-g laboratory environment.

The strawman design standards were substantiated very well with results from WETF EVA evaluation and Robotic Testing. It is very achievable to design interface structure to be equally friendly for both EVA and robotic operations. Highly structured and stiff interface members are needed to be compatible with robotic systems. There appeared to be minimal design influence on the ORU design standards when the robot is operated in a master/slave mode, rate control mode, or an autonomous mode.

Recommendations

The results of this initial study have identified the need to develop a standard ORU exchange system that is compatible with EVA and EVR operations. The process of developing these standards should include strong interaction with the work package designers and an extensive testing program. Some specific recommendations include:

1. Form an External Maintenance Task Force to develop, test and implement ORU specific hardware design standards.
2. EVA/EVR compatible tools and interfaces should be provided as Government Furnished Equipment (GFE) to each Work Package and International Partner.
3. Refine the Box Type ORU Strawman Standards and develop standards for other types of ORU's.
4. Continue to develop and test ORU mock-ups as part of the process of establishing ORU specific hardware design standards.
5. Determine the cost and benefits of different types of standardization.
6. Develop external maintenance procedures which minimize and optimize the roll of the on-orbit crew through the use of ground control and automated subroutines.
7. Develop a common EVA/EVR ORU exchange tool.
8. Investigate common ORU interfaces across the entire use cycle from ground storage to space station and return.

These recommendations are discussed in more detail below.

Task Force

A strong, high-level NASA Task Force should be formed with a charter to develop standards and specifications, organize external maintenance activities, and bring about the integration of EVA/EVR/IVA and ground control for external maintenance of the Space Station Freedom. This organization should perform an on-going function of integrating maintenance activities into the design and operation activities of SSF, monitor, direct, and assist the work packages' and international partners' activities to ensure compliance with the standards developed by the Fisher Price EMTT.

Standards

The Strawman Standards for Box Type ORU's developed initially by the EMTT at the Fisher-Price Mid-Term Review, should be developed, expanded, and applied to other types of ORU's. The standards should be implemented as specific hardware items (i.e., fasteners, soft dock, mechanisms, tool interface, etc.) that the ORU designers must incorporate directly into their designs.

Trade Study

A trade study should be initiated to highlight the impacts of imposing a standard ORU configuration on the work packages and international partners. The focus of the study should address development and life-cycle cost, weight, and schedule implications.

Tools

A common EVA/EVR ORU handling and torque tool should be developed. A single torque tool adaptable for EVA and EVR could potentially lower development and manufacturing costs while increasing task performance efficiency through familiarity.

ORU Mock-Up Design and Testing

The development of a generic Box Type ORU should be continued and used as a mechanism to develop and test design standards before imposing them on the rest of the Space Station Freedom Program.

It is recommended that an on-going test and evaluation program be implemented in support of standards development.

Concluding Remarks

A development program to evaluate the EVA and robotic compatibility of tools and ORU is needed to provide the proper guidance to the work packages and international partners for the detail design and manufacture of their ORUs. This program should be staffed and operated out of JSC using qualified, experienced staff and contractors. Testing and evaluation can be accomplished on site using astronauts and robots in a minimal time period.

It is recommended that mission models be constructed which address different scenarios of EVA/IVA/EVR, ground control, and supervised autonomous operations. The objective is to identify the area that results in the greatest reduction of on-orbit crew resources required for maintenance.

Commonality and compatibility between work packages in the "Box Type" ORU's design was found to be lacking. A better understanding of the operational characteristics of robotics and their interfaces is necessary to the success of this program. An on-going program to establish and maintain technical as well as program direction between all work packages and international partners must be established and centrally controlled.

Success of Space Station Freedom depends on the ability of the astronauts, robots, and ground-based support team to support station operation and maintenance. Integration and standardization of systems and system components, coupled with high reliability will minimize the external maintenance requirements. Early, rather than later, implementation of the EMTT EVA/EVR ORU standards will provide minimum cost impact on the program. EMTT standards appear to impose a minimum weight impact to SSF ORUs. The majority of the standards developed by the EMTT can be applied to other types of ORUs.

Acknowledgments

Development of the Strawman ORU Specification was accomplished through the cooperative efforts of the following work package international partner representatives:

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Martin	Jeff Paser
MDSSC	Mark Berlan Robert Lambeck Bob Mason Lou Ramon
NASA/GSFC	Paul Richards
NASA/JSC	Sue Burns John Chladek Jack Humphries Jose G. Limbardo Larry Ratcliff Gordon Rysavy Roger Schwarz LeBarian Stokes Charles E. Whitsett
NASA/MSF	Charles Cornelius Jack Stokes
NASDA/TOKYO	K. Shiraka
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Rocketdyne	Dave Blacklear Bob Dietzler
RSOC	Bob Adams Oscar Koehler Wayne Wedlake
SPAR	Frank Mee
TRACOR	Robert Radtke

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7. EVA Tools and Equipment NASA/JSC-20466
8. OSE Study Report OSE/MDSSC-SSD

Application of the Space Station Freedom Robots to Maintenance

Appendix H1

July 1990

Application of the Space Station Freedom Robots to Maintenance

Summary

The functional charter of the Space Station Freedom (SSF) robots is to provide support to the assembly, servicing, and maintenance operations of the Space Station and its payloads. The SSF robots have been evaluated and found to be a worthwhile resource capable of assuming most of the maintenance workload by the time the station is completely assembled, provided that proper consideration for robot compatibility is accounted for in the ORU design process. Information accrued and generated during the External Maintenance Task Team's (EMTT) evaluation of the SSF robots is presented in this appendix. Included in the various subsections are a general description of robotics and space-unique robots, detailed descriptions of the Flight Telerobotic Servicer (FTS) and the Mobile Servicing Center (MSC) and their applications to maintenance, the results of an analysis of a set of typical robotic ORU replacement tasks, and the identification of the significance of robot autonomy in relieving the on-board crew maintenance workload. A summary of the robotics recommendations is as follows:

Robotics Recommendations

1. Rely on SSF robots to accomplish a majority of the external maintenance workload by Assembly Complete.
2. Define, adopt, and enforce program-wide ORU/robot compatibility design standards.
3. Define, adopt, and enforce program-wide ORU worksite accessibility standards.
4. Implement an on-board collision avoidance capability in the MSC.
5. Implement a ground-based SSF geometry electronic database ("world model") for uplink initialization of on-board local robot workspace geometries and collision-avoidance algorithms.
6. Implement ground-based remote control of SSF robots for monitoring and control of all robot automatic functions.
7. Implement a rigorous verification program for all robotic functions with special emphasis on all automatic functions.
8. Implement a "robot repair of robots" policy to ensure that maximum utility of robots is achieved with a minimum of extravehicular activity (EVA) expenditure.
9. Integrate the use of all SSF robots (the U.S. Mobile Transporter, the U.S. Flight Telerobotic Servicer, the Canadian Mobile Servicing Center and Special Purpose

Dexterous Manipulator, and the Japanese Large Arm and Small Fine Arm) both as maintenance agents and as receivers of maintenance.

10. Begin analyses of SSF robots (as a group) performing multiple serial and multiple concurrent tasks for the purpose of optimizing robot and crew efficiencies.
11. Begin analyses of the use of the teaming of SSF individual robots and sets of robots with EVA astronauts for the performance of maintenance tasks to optimize the efficiencies of the combined set of human and machine maintenance agents.
12. Evaluate the benefits of the use of ground-controlled robots early in the assembly time period in between Shuttle flights to accomplish the maintenance tasks required.
13. Perform all inspections of exterior surfaces through an optimized combination of truss-mounted closed circuit television cameras, the SSF robot cameras, and the use of the SSF robots to position any additional inspection sensors identified in the future.
14. Design all EVA equipment to be robot-compatible ORUs to facilitate robotic assistance prior to, during, and after periods of EVA.

Introduction

Three major requirements for robotics applications to the maintenance of SSF have been identified by the EMTT study: replacement of robot-compatible ORUs, inspection of passive structure, and support of EVA astronauts during maintenance operations.

The ORU Database assembled by the EMTT indicates that over 8,000 ORUs are currently planned for Space Station. The analysis to determine the degree to which most of these ORUs can be made compatible with robot servicing remains to be completed, but leading efforts by Work Package 4/LeRC and Canada have concluded that 82 and 67%, respectively, of their ORUs are robot compatible. The FTS is reported to have 80% of its ORUs robot compatible, and Work Package 3/GSFC and the Level II User Payloads Office are reporting 100% robot-compatible components. While admittedly, there are some ORUs that are difficult to make robot compatible, such as cables, thermal blankets, and buried mechanism components, it appears that at least half, or perhaps as much as 80%, can be made robot compatible.

It should also be noted that ORUs can be made compatible with both the robots and the EVA astronauts for maintenance purposes. The design effort reported in Appendix G involved all work package and robot designers and produced a typical ORU design of this concept. A mockup of this design was built and was evaluated in Weightless Environment Training Facility EVA procedures and in the robotic laboratories at the Johnson Space Center. This type of ORU was also simulated and evaluated in the end-to-end robotic task timeline analysis that is reported in Appendix H4. The results of all of these efforts indicate that ORUs of this type can be replaced by either the robots or the EVA crew in a straightforward manner.

Requirements for inspecting the SSF passive structure are addressed in Appendix E. This inspection process has been identified as a boring and repetitive task. A scanning function, meeting all the inspection tasks that will eventually be identified, probably can be accomplished through the use of a combination of the eight truss-mounted television cameras and the cameras on the SSF robots. If sensors other than television cameras are required for specialized inspection, the robots can provide the mobility for those sensors.

Interactive support of EVA during Shuttle missions by teleoperation of the Remote Manipulator System (RMS) has proven to be very effective. Similar use of the Space Station Remote Manipulator and the Astronaut Positioning System for Space Station EVAs can be expected to simplify EVA crew mobility especially in the local space about the worksite. Benefits of this kind of EVA support by the robots cannot be quantified at this time because the simulators and test facilities required to determine this information are still in development.

For similar reasons, analysis of the interaction of the other SSF robots in support of an EVA crew has not been addressed during this study except for considering use of the robots to set up the worksite prior to a crew EVA. Installation and removal of EVA worksite support equipment are very similar tasks to those asssociated with ORU replacement. These equipment items can be made robot compatible, and, therefore, can readily be accommodated by the robots. Installation of the EVA portable workstation at the single worksite by the robots has been found to save 36 minutes of EVA time.

Robots and Teleoperators

Robots are powered machines the utility of which is based on the extent to which they can properly change the workspace in which they are put to perform a function. Industrial robots are very effective in performing repetitive tasks such as spray painting and welding automobiles on assembly lines. These robots are taught on a point-by-point basis where they should move and direct a spray gun or welder and when to trigger these tools. This is the simplest form of robot automation: the robot will repeat the same path or trajectory of its end-of-arm tool for as long as it is powered. Performance by this kind of automated robot is effective as long as the workspace remains well structured. However, the robot has no sensitivity to changes in the workspace; it operates open loop, i. e., without sensory feedback from the workspace. If a different style automobile (e.g., a truck instead of a sports car) is presented to it by mistake, the robot will attempt to spray the same pattern or weld the same bead and will very likely damage the truck and itself as well.

A teleoperator is a powered machine under continuous control by a human operator whose utility can be measured in the same manner as a robot, with the exception that the skill and training of the human are significant factors in the overall effectiveness of the teleoperator. The genesis of teleoperators in the robotics community was in the nuclear industry in the 1950's when mechanical hands were operated in hot cells and were controlled under the explicit direction of a human at a safe, shielded distance. The major advantage of a teleoperation system is that it can readily accommodate changes in the workspace. Since the human operator is always present, changes in the geometry or content of the workspace can be observed, and adjustments can be made in the motion of the robot arm.

The Space Shuttle RMS is the only operational space robot. It can perform both as a teleoperator and as an open-loop automated robot. For most procedures, the RMS is used as a teleoperator with an astronaut operating it with the hand controllers in the Shuttle aft flight deck. Tasks routinely achieved using the RMS include deployment of payloads, retrieval of satellites, support and transport of EVA astronauts, and local illumination and inspection by closed circuit television of the Shuttle and payloads. On occasion, the RMS has been commanded to operate using stored trajectory points in an automated fashion. These trajectory points are developed and intensely analyzed preflight using highly sophisticated ground simulations. The most recent example of a stored trajectory command was the pitchover maneuver for the Hubble Space Telescope prior to its deployment. The RMS has been flown on 21 flights. On each of these missions, it was operated under the constant watchful eyes of an operator and an on-board observer, with ground controllers performing additional constant monitoring.

Space Station Freedom Manipulators and Robots

The SSF robot team consists of five major robotic devices contributed from three countries. These robots offer a wide variety of both common and unique capabilities. All robots will be electrically powered, servo-stabilized articulated mechanisms that can be controlled by the astronauts from inside the Space Station. All will be instrumented and interfaced to the on-board data management system to provide monitoring data for the on-board crew and ground controllers. All will have computational capabilities to support complex control algorithms. All of the devices will carry their own television cameras. Four of the devices will be transportable and able to perform work throughout SSF. Four of the devices will be designed to accommodate upgrades in robotics technologies. None of these robots will be free flying.

A fundamental figure of merit for a robot is its number of degrees of freedom, which is equivalent to the number of commandable joints. For reference, the Shuttle RMS has six degrees of freedom.

The U.S.-provided FTS will be a two-armed robot with a stabilizing leg that will be capable of dexterous manipulation in both free motion and constrained space. The FTS will have 19 degrees of freedom and will be capable of being positioned at a worksite to operate independently of the transporter mechanism. The FTS will be operated as a force reflective teleoperator; i.e., it will provide feedback to the operator when contact is made by the FTS with a structural object. The FTS will be capable of workspace modeling and calculating collision avoiding paths and trajectories. A more thorough description of the FTS is found in Appendix H2.

The U.S. will also provide the Mobile Transporter (MT) for SSF. The MT will be capable of movement along and around the five-meter truss bays. The MT will have two articulated arms that will be used for positioning the EVA astronauts similar to the way the Shuttle RMS is used to position the EVA crews. The MT will be used to transport the FTS and the Canadian-provided robots to worksites about the Space Station. The MT will have 13 degrees of freedom.

Canada will provide the MSC which will consist of three major components. The Space Station Remote Manipulator System (SSRMS) is a second-generation remote manipulator arm. With 7 degrees of freedom, the SSRMS will be 57-feet long compared to the 50-foot length of the Shuttle RMS. The SSRMS will primarily operate off of the Mobile Base which will be attached to the MT, but the SSRMS will also be capable of detaching itself from the Mobile Base and "walking" about the Space Station on special power data grapple fixtures. Unlike the Shuttle RMS, the SSRMS will be fault tolerant, capable of sensing forces and movements, and capable of calculating collision-free paths.

Canada will also provide a 19-DOF Special Purpose Dexterous Manipulator (SPDM) which will be operated on the end of the SSRMS or independently from the power data grapple fixtures. The primary purpose of the SPDM is to provide robotic servicing of the SSRMS, but it also will be effective in providing general maintenance support. The SPDM is a two-armed robot with 19 degrees of freedom that will be capable of dexterous manipulation and machine-vision updates to the world model that will be used in the collision-avoidance algorithms of the SSRMS and the SPDM. A more thorough discussion of the Canadian robots is found in Appendix H3.

Japan will provide a compound robot consisting of a 7-degree-of-freedom Large Main Arm topped with a 7-degree-of-freedom Small Fine Arm that together will reach about 25 feet. These robot arms will be permanently attached to the Japanese Experiment module for servicing the Japanese experiments. These robots currently are not expected to contribute significantly to overall SSF maintenance.

General Observations

It is evident that SSF will have a considerable amount of robotic capability, the value of which is only beginning to be understood by the SSF design community. Because of popular movies exhibiting erudite, charming, and agile robots, the general public may have expectations of robot performance that far exceed what can be implemented on SSF (or anywhere else). Availability of intelligent, genuinely autonomous robots that can be relied on for days of unattended productive operation in a widely variable environment is still far in the future. It is, however, being intensely researched today by NASA, academia, and industry. An inescapable fact is that any increase in the level of robot autonomy carries with it an attendant premium of high computational capability required.

Since the lifespan of SSF extends 40 years into the future, the SSF robots may eventually include the kinds of robust, autonomous functions that are being studied in the research labs now. Nonetheless, the currently planned early capabilities of the SSF robots still can be applied beneficially to the external maintenance of the Space Station both to avoid EVAs and to make them more productive. Designing the ORUs to be robot and EVA compatible is critical to managing SSF external maintenance; there is still adequate time, however, in the design cycle to do this.

Given robot-compatible ORUs, the baseline SSF robots can be used to accomplish a majority of the maintenance required by the time the Space Station is completely assembled. The level of efficiency, however, is limited by the current lack of collision-avoidance capability. This software function requires the commitment of two on-board standard data processors during the time that this part of the MSS is active. The benefit of collision avoidance is fourfold:

- It makes the teleoperated procedures for positioning the robots and the ORUs shorter in time by providing to the operator advisory information on the collision-free workspace.
- It reduces the training time required for the operators to become proficient.
- It enables the automatic sequencing of the positioning processes.

- It prolongs the life of the robots by both reducing their duty cycles and the unnecessary wear on robot joints associated with the less optimized trial-and-error procedures.

Adding ground control to the program offers the alternative of relieving the on-board crew of all of the robotically conducted maintenance. Robot-compatible ORUs and collision avoidance must be included first, however, to enable the use of ground control with the more difficult robot operations.

Given robot-compatible ORUs, collision avoidance, and ground control, the long-term external maintenance of SSF is manageable. External maintenance prior to assembly complete, however, is more problematical since the SSF configuration changes as each sequential Shuttle mission adds components to SSF. A major crew timeline analysis of maintenance, similar to the one reported in Appendix H4 should now be initiated to investigate the effectiveness of the SSF robots in performing maintenance before the Space Station is completely assembled.

Application of the Flight Telerobotic Servicer to Space Station Freedom Maintenance

Appendix H2

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July 1990

Appendix H2
Acronyms and Abbreviations

ASPS	Attachment Stabilization and Positioning System
CETA	Crew and Equipment Translation Aid
DOF	Degree of Freedom
EMTT	External Maintenance Task Team
EVA	Extravehicular Activity
FEL	First Element Launch
FTS	Flight Telerobotic Servicer
GSFC	Goddard Space Flight Center
JSC	Lyndon B. Johnson Space Center
MSC	Mobile Servicing Center
MT	Mobile Transporter
ORU	Orbital Replacement Unit
SAE	Storage Accommodation Equipment
SIA	Structural Interface Adapter
SPDM	Special Purpose Dexterous Manipulator
SRMS	Shuttle Remote Manipulator System
SSF	Space Station Freedom
SSRMS	Space Station Remote Manipulator System
TR	Telerobot
WAF	Work Site Attachment Fitting

Application of the Flight Telerobotic Servicer to Space Station Freedom Maintenance

The Flight Telerobotic Servicer (FTS) project began in 1986 when Congress asked NASA to develop a telerobotic system as part of the Space Station Freedom (SSF) automation and robotics program. The NASA Goddard Space Flight Center (GSFC) in Greenbelt, Maryland, is responsible for managing the FTS development program. The FTS prime contractor is Martin Marietta Corporation in Denver, Colorado. The five major objectives of the project are 1) to reduce space station dependence on crew extravehicular activity (EVA), 2) improve crew safety, 3) enhance crew utilization, 4) provide remote servicing capability for platforms, and 5) accelerate technology transfer from research to U. S. industry. Six baseline tasks were defined to establish the required FTS capabilities at SSF first element launch (FEL). These tasks are

- installation and removal of truss members
- installation of a structural interface adapter (SIA) on the truss
- changeout of SSF orbital replacement units (ORUs)
- mating of the SSF thermal utility connectors
- assembly and maintenance of SSF electrical power system radiator assembly

Currently, specific SSF assembly tasks have been assigned to FTS for evaluation against these capabilities.

Two test flights – a Development Test Flight (DTF-1) and a Demonstration Test Flight (DTF-2) – precede the deployment of the initial operational FTS system at FEL in 1995. DTF-1, scheduled for flight in 1991, will validate the performance of the FTS manipulator design in a zero-gravity environment. Data obtained will also be used to evaluate human-machine interfaces and correlate system performance in space with ground simulation and analysis. DTF-2, scheduled for flight in 1993, will validate the full task capabilities of the FTS. Following DTF-2, the DTF-2 flight hardware will be refurbished, updated as required, and delivered to GSFC to be installed as an engineering test system to support operation and evolution of the FTS.

Flight Telerobotic Servicer Description

The FTS system shown in Figure H2-1 consists of the telerobot, both Shuttle and Space Station workstations, and an on-orbit storage accommodation equipment facility.

The FTS telerobot shown in Figure H2-2 has two manipulators, each with seven degrees of freedom (DOF) and a wrist-mounted camera. It also has a single five-DOF attachment stabilization and positioning system (ASPS) mounted on a compact body. The body contains internal electronics that provide power, data management, processing, and communication functions. The internal components, manipulators, and ASPS are modular ORUs to enhance the maintainability of the FTS. Also mounted on the body are two Ku-band antennas for communication, a camera-positioning assembly with two head cameras, and holsters for storing tools and end effectors. At the outboard end of each manipulator is an end effector changeout mechanism that provides mechanical and electrical interfaces for a variety of interchangeable tools.

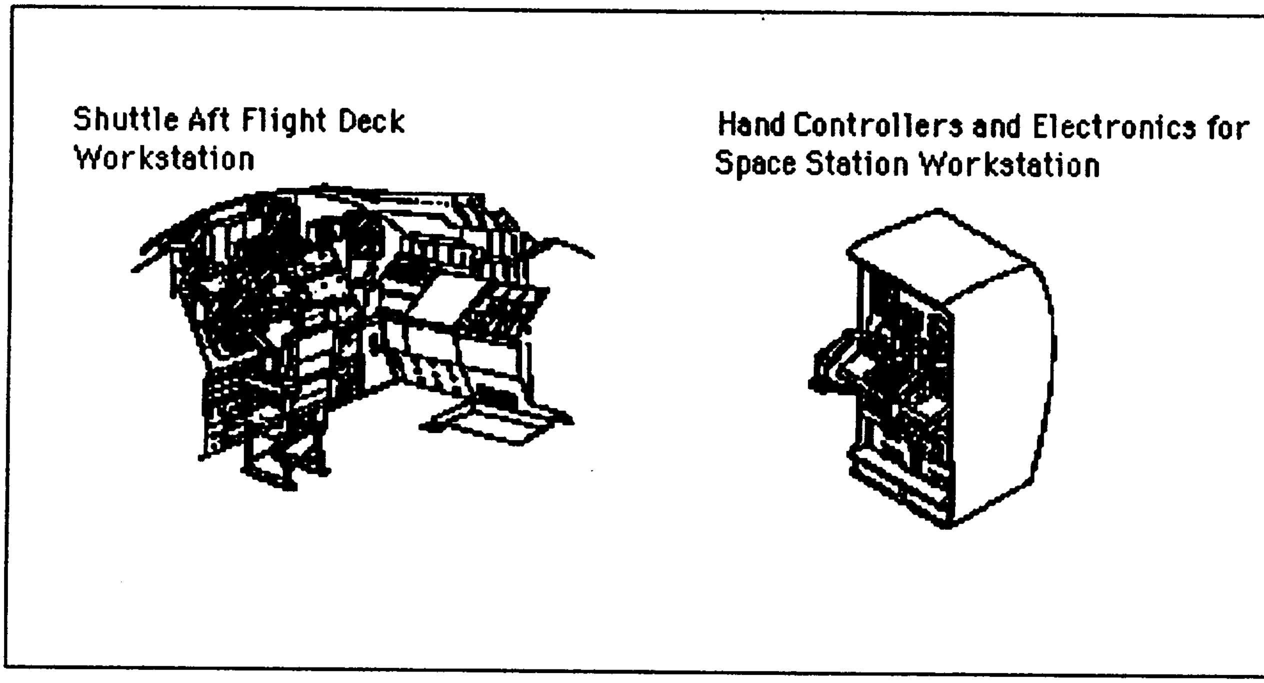

Figure H2-1. Flight Telerobotic Servicer Elements

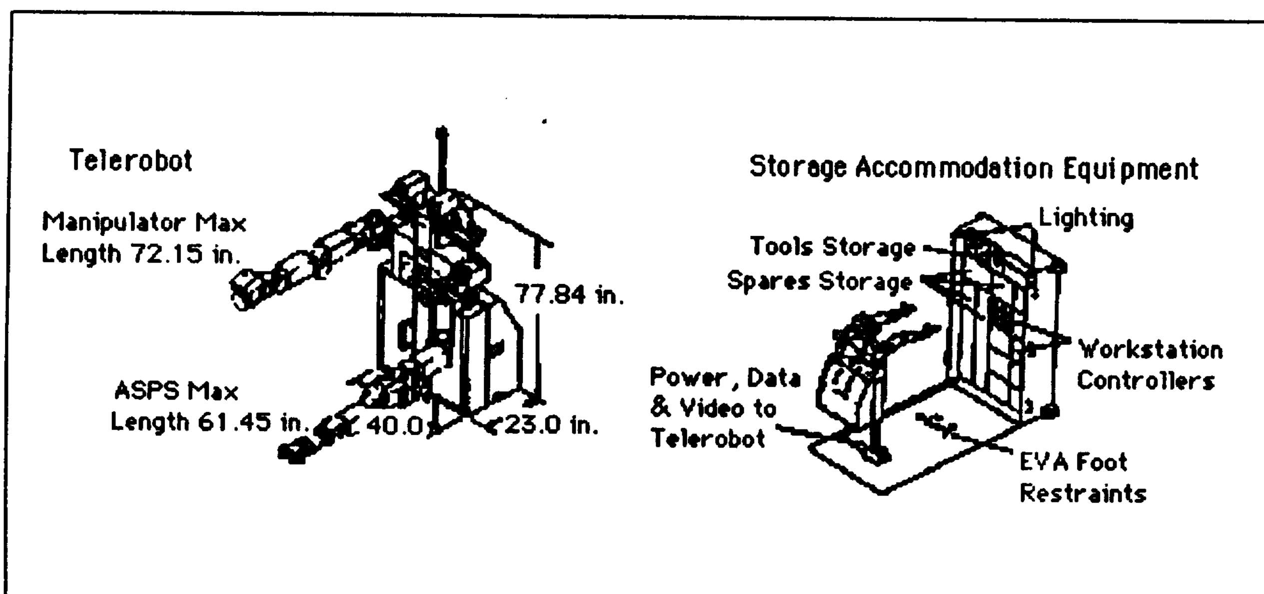

Figure H2-2. FTS Telerobot Elements

The Shuttle and Space Station workstations will provide the operator with similar interfaces, including color video displays, text and graphics overlay capability, and two six-DOF force reflecting hand controllers for teleoperation of the FTS manipulators. During operation, a sequence of events is displayed which the operator will use as a checklist. As commands are issued, displays provide status information, command menus, and system schematics. Anomalous events result in alert messages to the crew providing automatic caution and prioritized warnings.

The FTS will be stored on orbit at a storage accommodation equipment (SAE) facility which will be attached to the Space Station truss structure on the nadir facing side of the truss. The SAE provides for storage of the telerobot; storage of FTS ORUs and tools; a power, data, and video interface with the space station; and an EVA station to support EVA maintenance of the FTS.

The FTS has three operating modes: dependent, transporter-attached, and independent. In the dependent mode, the FTS is attached via the ASPS to an FTS-improved worksite with full utilities available through the worksite attachment fixture (WAF), or at unimproved worksites with utilities provided through an umbilical to a nearby utility port. Utilities include power, data and video. In the transporter-attached mode, the telerobot is attached to a Shuttle remote manipulator system (SRMS) or Space Station remote manipulator system (SSRMS) via a grapple fixture mounted on the back of the FTS body. Utilities are provided either directly through the grapple fixture or through an umbilical. In the independent mode, the FTS will derive power from internal batteries with data and video interfaces provided through the Ku-band antenna. If an appropriate mechanical attachment is available at the worksite, the independent mode provides the flexibility to perform tasks at worksites without utilities.

Flight Telerobotic Servicer as a Maintenance Agent

The FTS provides a versatile capability for long-term SSF maintenance. Primary maintenance activities will consist of ORU replacement and inspection tasks. FTS can perform maintenance while attached to the SSRMS, from improved FTS worksites positioned on an FTS WAF, or from unimproved worksites in independent operation mode. This versatility allows the FTS access to practically the entire Space Station. It should be noted that the FTS can be left at improved worksites for extended periods if necessary. This capability allows resources such as the Mobile Servicing Center (MSC) to be freed up for other activities, such as transport of ORUs and the Canadian Special Purpose Dexterous Manipulator (SPDM) to another worksite, while the FTS continues operation or suspends operation while other activities are underway. This mode of operation can also be used for long-term observations.

The SSF maintenance philosophy is based on the concept of ORUs. When a component fails, the ORU which contains that component is replaced as a unit to effect repairs. All SSF ORUs designated for robotic replacement must be designed to be compatible with astronaut EVA replacement and robotic replacement. The key to maximizing the FTS maintenance capabilities is providing robotically compatible ORU designs and access to the ORU locations. Robotic compatibility includes the design of fasteners, connectors, grasp points, and alignment aids (both visual and mechanical) as well as providing adequate access at worksites for the FTS system. Robotically compatible ORU designs should also increase the efficiency of EVA maintenance activities on the same hardware. The present SSF design requires changes to accomplish robotic compatibility in those areas where robotic maintenance will be a requirement. In many cases, particularly for the box-type ORUs, the designs are not mature, and achieving robotic/EVA compatibility should not be difficult. In other cases relating to ORU access, a different arrangement of the ORUs must be made for efficient, safe, and ultimately autonomous access by the SSF robots.

The FTS is also well suited for a variety of inspection tasks. Using either the wrist cameras or head cameras, the intravehicular activity (IVA) operator can use the FTS to perform visual inspection of worksites for confirmation of maintenance or assembly results, visually check electrical and fluid installations and connections, and visually inspect for physical damage to any component of the Space Station. Using special purpose sensing devices, inspections can include temperature probing and leak checking of fluid systems.

The FTS system can also be used to assist in the changeout of large SSF hardware which is primarily positioned using the SSRMS. The FTS can be placed at the worksite in either dependent or independent mode to attach/detach the hardware and provide positioning assistance as the SSRMS is used to remove or replace the large hardware item.

The FTS is designed to provide dexterous manipulation of objects up to approximately 1200 pounds. Basic performance characteristics include:

- generation of a minimum of 20 pounds of force and 20 foot-pounds of torque at the manipulator tool plate anywhere within the manipulator workspace
- unloaded tool plate velocity of 24 inches per second.

The characteristics that allow for full or partial autonomous maintenance activities are:

- absolute positional accuracy of <1.0 inch in position and <3.0 degrees in orientation
- repeatability under constant thermal conditions of <0.005 inch in position and <0.05 degrees in orientation.

The primary FTS tool is a dual purpose end effector which provides a parallel jaw gripper function with interchangable fingers and a rotary tool function with interchangable rotary tools. Interchangeable fingers and rotary tools allow compatibility with a variety of possible mechanical interfaces. The end effector changeout mechanism allows exchange of the entire end effector to allow use of special purpose tools. The FTS end-of-arm tooling system is depicted in Figure H2-3. As a goal, FTS tools will be designed for common interfaces with EVA and SPDM tools. It is also a goal to minimize the number of tools by standardization of the interfaces. Program direction is required to achieve these latter two goals and work has commenced to begin that process.

A number of preliminary computer graphic simulations of the FTS performing maintenance tasks were performed at the NASA Johnson Space Center (JSC) during the External Maintenance Task Team study. These efforts were supported by NASA GSFC and Martin Marietta Corporation, the FTS prime contractor. The simulations showed that while the tasks could be determined to be performed in terms of reach and access, difficulties did arise that indicated that ORU hardware design iterations, as well as robotic design iterations, will be necessary to achieve efficiency. Particularly, a more structured environment at the worksite is required to achieve the full potential of autonomous robotic maintenaance activities.

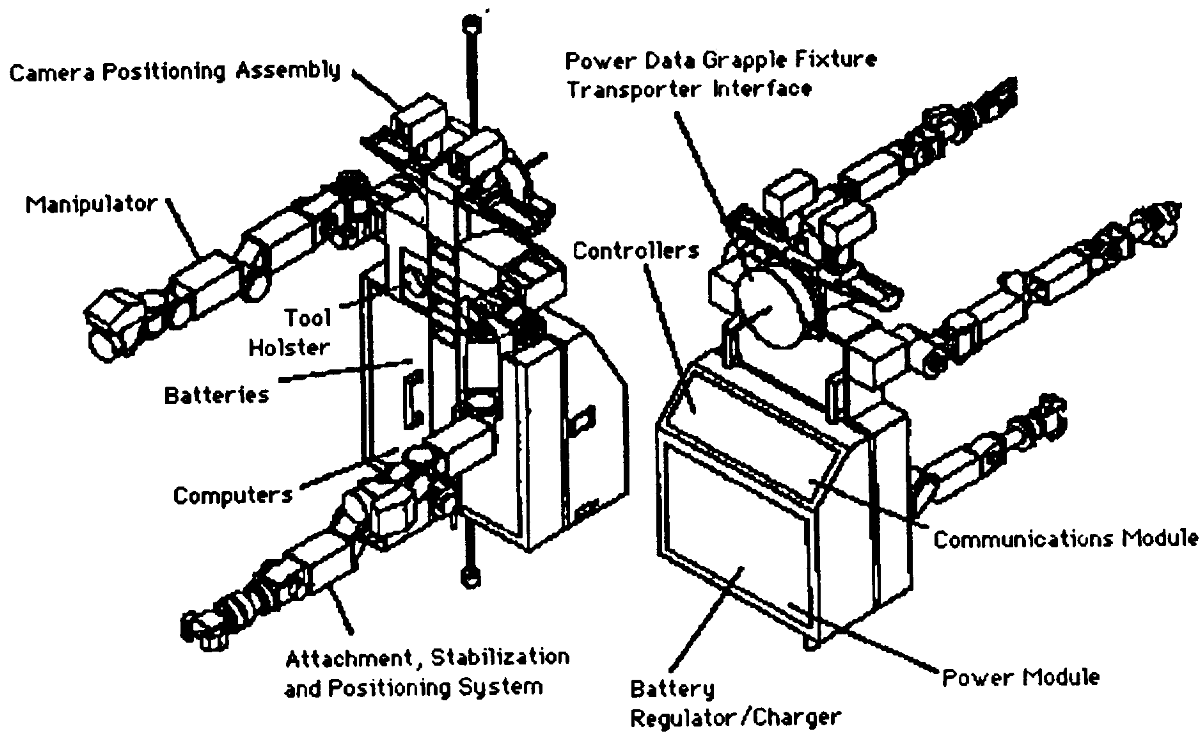

Figure H2-3 FTS End-Of-Arm Tooling System

Relationship of the Flight Telerobotic Servicer to the Mobile Servicing Center (MSC)

The FTS is dependent on the MSC for mobility along the Space Station truss. The MSC must be fitted with a WAF to provide a base for the FTS during transport to and from maintenance worksites. The FTS will be provided all utilities at this WAF to allow system operational checkout and verification. The FTS can perform maintenance activities from this MSC WAF provided the maintenance article is reachable from this site, or the Space Station RMS (SSRMS) has brought a maintenance item to the FTS. With proper placement of the FTS WAF on the MSC, the FTS could access MSC and mobile transporter (MT) ORUs as a backup to the SPDM for MSC component maintenance.

In a representative maintenance scenario, the MSC would travel to the FTS SAE where the SSRMS would grapple the FTS and transport the FTS to the MSC WAF transport position. The MSC would then travel to the unpressurized logistics module where the replacement ORU would be obtained. This would require the SSRMS to grapple the FTS from the MSC WAF and transport the FTS to the location of the replacement ORU where the FTS would detach the ORU. The SSRMS would then return the FTS and the replacement ORU to the MSC where the FTS would either attach the ORU to a transport location or maintain possession of the ORU for transport. The MSC would then provide transportation to the worksite for both the FTS and the replacement ORU.

At the worksite, the SSRMS provides transport for the FTS from the MSC to the actual maintenance location. The FTS then either performs maintenance functions while attached to the SSRMS or can be positioned at the worksite which frees the SSRMS for other activities. If possible, the FTS carries the replacement ORU into the maintenance location and performs the ORU removal and replacement in a single trip. Optionally, the SSRMS positions the FTS for ORU removal; returns the FTS with the old ORU to the MSC for attachment of the old ORU and retrieval of the replacement ORU; returns the FTS with replacement ORU to the maintenance location where the FTS installs the replacement ORU; and then returns to the MSC. The use of an ORU pallet that is placed within the reach of the FTS when the FTS is positioned at the worksite on its ASPS may alleviate the number of steps required in the ORU replacement scenario.

The reverse of the initial sequence is executed for returning the FTS and the defective ORU to their respective storage sites.

It is clear that the MSC transportation and positioning of the FTS is key to FTS maintenance activities as currently envisioned. Additional forms of mobility for the FTS, such as FTS use on a crew and equipment transfer aid (CETA) cart, should be investigated to increase the FTS effectiveness for maintenance activities by decreasing the dependence on the MSC for all transportation activities.

Relationship of the Flight Telerobotic Servicer to the Flight Crew

The flight crew has two principal interactions with the FTS. The first is internal to the SSF at the workstation. Here, the operator controls the telerobot from a workstation which consists of a set of hand controllers, two or more video displays, a data display, a keyboard, and a voice recognition system.

The hand controllers are the primary means for effecting manual control of the telerobot manipulators. With force feedback, the crew operator can actually "feel" the forces imposed on the task hardware. Force feedback allows the operator to compensate for unwanted forces and torques such as those generated by misalignments during ORU removal and replacement or connector mate and demate operations. Force reflection may be switched on and off by the operator. Gains for translation, rotation, and force reflection are also variable over wide ranges. The hand controller is inherently easy to use since it supports an intuitive relationship between the operator's movements and those of the manipulators. The system can be "indexed" to redefine the relative reference frame between hand controller and manipulator. This allows for individual tailoring of the relative displacements of master and slave for collision avoidance, precise end effector control, or operator envelope definition. The hand controllers work in either a bilateral position control or a rate control mode, selectable by the operator. Several mixed modes which include partial autonomous control are also available. Also under consideration are mixes of rate and position control modes (e.g., using position control for translations and rate control for rotations).

The video displays provide the operator with views of the worksite through cameras mounted on the telerobot itself or from other cameras which may be available at the worksite. These views give the crew operator a "presence" of the task surroundings, the

ORU, and the FTS tools. Telerobot video is provided by four separate cameras and associated lighting. The telerobot has two "head" cameras, located to the left and right of the telerobot's centerline. These cameras are independently translatable from their centermost position to a position over each shoulder. These cameras each have pan, tilt, and zoom capability and are used to provide views of the worksite and manipulators. These camera views are used primarily for gross alignments of the manipulators and task panel components, and to verify the orientation of manipulator joints. The operator will use these views when operating the system in a telerobot body-referenced coordinate system. Wrist cameras, attached to each manipulator wrist, provide a closeup view of the worksite. They are located at the wrist's roll joint, so that, as the wrist is rolled the camera view of the worksite is rolled as well. This configuration facilitates the use of these views when the operator is operating in an end effector coordinate reference frame. The operator controls the cameras through the voice recognition system by vocalizing commands like, "LEFT HEAD CAMERA.....PAN LEFT.....STOP." The use of voice input allows the operator to command the vision system while both hands are busy with teleoperation activities, thereby reducing the need for dedicated workstation controls, hand controller switches, or additional operational display screens. Backup control of all of these functions will be provided through the operational display and the use of the variable function keys and/or keyboard.

The data display provides the operator with the means to monitor telerobot health and status, current operational parameters, and other data pertaining to the task being performed such as manipulator position/rotation, joint angles, selected camera views, etc. The keyboard provides the primary means for the operator to interact with the telerobot system in order to perform such tasks as selecting system control modes and other parameters, resetting limits, initiating task sequences, acknowledging messages, and selecting and displaying different camera views and controlling the cameras. The primary purpose of the voice recognition system is to provide the operator with a means of interacting with the FTS system to select and control the cameras without removing his/her hands from the hand controllers. The ability to use the voice recognition system to perform other interactions such as changing control defaults, selecting different data displays, and other such control actions normally provided through the keyboard is being studied.

A typical operational display contains checklist information for performance of tasks, control parameters that are frequently changing during task steps, and additional "soft" buttons (operated with variable function keys) for executing commands required for performance of the task. Engineering displays will be used to display subsystem health and status information required for system monitoring or anomaly investigation. These displays will be accessed by the crew through keyboard entries. They will be accessed only when the crew is in an "off-line" mode (during system Standby mode). Specific display request identifiers and procedures will be provided to the crew through the hardcopy procedures provided in the flight data file or through directions from the ground.

The second FTS interaction with the flight crew occurs on the external Space Station structure and components. Here, the FTS and the crew act as a team. While not operating in the same work volume as an EVA crew member, the FTS can set up the worksite prior to crew egress and perform worksite cleanup after the EVA crew member has completed a task. Additionally, if a crew member has difficulty with completing a task, the FTS can hold items indefinitely until the crew member returns to the worksite. Choreography of task events in this cooperative EVA/FTS mode has not been explored to date, but will certainly come into play as a means of increasing EVA crew efficiency.

Flight Telerobotic Servicer as a Maintenance User

The general maintenance concept for the FTS program consists of three echelons of maintenance: 1) organizational, 2) intermediate, and 3) depot. Organizational-level maintenance will consist of corrective maintenance tasks that are required to restore the FTS to an operational status. This will normally be removal and replacement of failed ORUs. Intermediate level maintenance will consist of preventive maintenance actions and will include FTS upgrade modifications and selected repair of ORUs. Depot-level maintenance will consist of ORU repair which will be performed at a ground-based facility.

All spares for the FTS will be stored in the SAE, except the hand controllers, hand controller electronics, and any sub-ORU spares, which will be stored in the pressurized man-core storage area. The SAE is an unpressurized structure that is attached to the Space Station truss. Telerobot IVA maintenance, if required, will be performed at the Maintenance Work Station located in the U.S. Lab Module and will require passing the entire telerobot or manipulator through the SSF airlock.

Organizational-level maintenance will normally consist of removal and replacement of failed ORUs. A summary of the baseline organizational maintenance scenario consists of the following:

1. Anomaly is detected by the initialization or health and status software and reported to the operator by the operator control interface software.
2. The operator queries the operator control interface software to provide status of the fault and determine if the task can continue either in a degraded mode or via alternative methods.
3. If the task cannot continue, the operator performs fault isolation via the control interface software to determine which ORU contains the fault.
4. If the failed ORU is located in the SAE, an EVA astronaut or the SPDM is dispatched to effect repairs. The EVA astronaut passes through the airlock and proceeds to obtain the appropriate spare from the SAE. He or she then changes out the ORU and signals the FTS operator to perform a systems check to verify the repair.
5. If the failed ORU is located on the Telerobot (TR), the TR is retrieved from its worksite via the MSC and attached to the SAE. An EVA astronaut or the SPDM is then dispatched to effect repairs. The EVA astronaut passes through the airlock and proceeds to obtain the appropriate spare from the SAE. He or she changes out the ORU and signals the FTS operator to perform a systems check to verify the repair. If the TR could not be detached from the worksite, the EVA crew member would transport to the worksite with the appropriate spare via the MSC or CETA and effect repairs.
6. If the fault is located in the TR, but cannot be corrected by an ORU changeout, or as an option to ORU replacement, the TR can be brought into the U.S. Lab Module for repair. This will require an EVA astronaut to retrieve the TR (or the MSC can bring the TR to the airlock), stow the stabilizer/manipulators and position the TR through the airlock.
7. If the fault is located in the hand controllers or hand controller electronics, the defective ORU will be replaced by the operator with a spare which is located in the SSF manned core storage area.

Other maintenance strategies are under investigation including robotic exchange of selected high maintenance ORUs and some robotic self-repair actions such as replacing lamps, lens covers, contamination sensors and crew warning devices. Table H2-I provides a list of the current FTS ORUs.

Table H2-1. FTS Orbital Replacement Units

Manipulator Computers	Telerobot Control
Telerobot Redundant Controller Electronics	Tool Holster/CPA Control
Workstation Control Computers	Storage Unit Controller
Storage Unit (Data Recorder)	Hand Controllers
Hand Controller Drive Electronics	Wrist Camera Assembly
CPA Head Camera Assembly	Camera Lamps
Camera Lens Covers	Camera Positioning Assembly
Crew Warning Device	Power Data Grapple Fixture
Umbilical	Umbilical Holster
Force Torque Transducer	Contamination Sensors
End Effector Holster	End Effector Base
Double V-Block Tool	1/2" Key Wrench
7/16" Socket	Worksite Attachment Fixture
Worksite Attachment Mechanism	Module Servicing Tool Holster
Tool Holsters	Radiator Panel Tool Holster
Node Attachment Tool Holster	Module Servicing Tool
Radiator Panel Tool	Node Attachment Tool
Power Module	Battery
Regulator/Charger Module	Communication Module
Antenna Assembly	ASPS

Automation of Flight Telerobotic Servicer Functions

Automation of simple and/or repetitive tasks will decrease operator workload and fatigue. Further increases in automation will elevate the operator to a supervisory role which could relieve the necessity for direct operator involvement for substantial periods of time, thereby increasing crew availability for other tasks. Increased automation also enhances the possibility of ground control of the FTS which again increases crew availability for other activities. The FTS is designed for evolution and growth from a predominantly teleoperated system to a highly autonomous system. It is the goal to automate repetitive and well- structured tasks while maintaining direct teleoperation capability for unexpected, new, difficult, or critical tasks where direct human control is desirable.

The selection of the NASA/National Bureau of Standards (NBS) Standard Reference Model for Telerobot Control System Architecture (NASREM) as the FTS functional architecture facilitates the evolution of the FTS from teleoperated machine to autonomous robot. NASREM defines a set of standard modules and interfaces based on hierarchical control levels which provide the software hooks necessary to incrementally upgrade the FTS as new capabilities develop in computer science, robotics, and automated system control.

Some autonomous capability will exist at FEL. The FTS will execute automated sequences which have either been preprogrammed on the ground or "taught" via the operator teleoperating the system through a sequence and storing the desired actions for playback as an automated sequence. An example of initial automated capability is the planned automated exchange of end-of-arm tooling. Such automated sequences rely on the manipulator repeatability performance to accurately position and orient the manipulator and tooling using alignment guides and active compliance to accommodate slight positioning and alignment errors during task execution. This form of automated function relies on a highly structured worksite and the known position of the manipulator with respect to the task.

To accommodate uncertainty in relative position of the manipulator and the task, sensing capability (specifically machine vision) must be incorporated within the manipulator control system. Such vision-based control requires targets at the worksite or readily identifiable worksite features from which to extract positional data to guide the manipulator to successful task completion. Updating the FTS system to incorporate machine vision capability requires software updates to the baseline FTS system. A vision-based control capability would allow the automation of most, if not all, box-type ORU replacements as well as other tasks with well-structured geometries and adequate access. An interim approach to the development of a full machine vision system consists of operator-assisted workplace identification. As an example, the operator could designate workpieces to the FTS at the beginning of a session through cursor control on the video displays generated from the FTS cameras. The FTS software would adjust its internal world model to the physical workspace and then proceed to perform the autonomous task.

Further automation includes automated path planning and automated task planning. Such capabilities are feasible through software additions to the baseline system using the NASREM architecture design. On-board path planning requires not only a path planning capability within FTS but also a pre-stored or real-time generated model of the worksite for the system to use in determining collision-free manipulator and tool paths. Task planning could remain a ground-based function with the resulting task scripts provided to FTS for execution.

Basic software technology currently exists in the form of laboratory systems which implement the algorithms necessary to provide substantial automation capabilities for the FTS. The use of the NASREM architecture will enable these technologies to be incorporated into the FTS as they mature. The FEL FTS software contains elements of the world modeling capabilities required for path planning within the initial collision avoidance software. Machine vision, vision-based control systems, path planning, and world modeling algorithms are all available in various stages of maturity. As part of FTS evolution, specific FTS needs will be identified and developed. Ground-based FTS systems available for testing and verifying automation capabilities will include FTS trainers which are hydraulic manipulators controlled via flight software. Also the DTF-2 flight system will be refurbished for use at GSFC as the Engineering Test System. Present delivery schedules for these ground hardware systems are

DTF-1 1-g Hydraulic Simulator	02/91
DTF-2 1-g Hydraulic Simulator	10/92
FTS 1-g Hydraulic Simulator	10/93
DTF-2 Refurbished as ETS	04/94.

These systems will provide ground testbeds within which to implement, test, and verify all FTS upgrades prior to flight use during the 30-year FTS lifetime. The DTF-2 1-g hydraulic simulator will be used to validate end-to-end task completion with full scale mockups of task hardware. Introduction of autonomy to tasks will involve introduction of software changes into the hydraulic simulator and execution of tasks with the changes. Verification of the flight software uploads will take place on the ETS flight system with emphasis on local task manipulations.

Recommendations

The External Maintenance Task Team study has focused attention on the total maintenance requirements of the Space Station across all SSF elements. Substantial reliance on robotic capabilities for maintenance is needed to increase crew availability for non-maintenance activities. Preliminary studies have indicated that robotic systems can provide the required capabilities; but, more detailed analysis and hardware testing must be performed to verify these conclusions. Several activities, some of which have already begun, must continue toward providing the verification needed to ensure the successful implementation of robotically compatible design features. All hardware designs for components which are proposed for robotic interaction must be thoroughly analyzed, prototyped and physically tested to verify robotic compatibility. Such an activity has begun for box-type ORUs to drive out specific design characteristics to provide guidance to SSF component designers. The types of issues which must be evaluated include

- visual cues, guides, and targets
- mechanical alignment guides
- soft-dock mechanism requirements
- attachment mechanism design and activation
- connector mate/demate mechanism

- handling fixtures
- lighting requirements
- camera views
- optimum position of robot relative to task-for-task execution

The final item will provide quantitative data for each task as to the access volume required for robotic execution of a task. Such comprehensive analysis and testing are required to maximize the benefits gained from the SSF robotic systems.

Application of the Mobile Servicing System to Space Station Maintenance

Appendix H3

David G. Hunter
Canadian Space Agency

July 1990

Appendix H3
Acronym List

APS	Astronaut Positioning System
EMTT	External Maintenance Task Team
LEE	Latching End Effector
MBS	MRS Base System
MCE	MSS Control Equipment
MFR	Manual Foot Restraint
MMD	MSS Maintenance Depot
MSC	Mobile Servicing Centre
MT	Mobile Transporter
ORU	Orbital Replacement Unit
PDGF	Power Data Grapple Fixture
POA	Payload ORU Accommodation
SSRMS	Space Station Remote Manipulator System
TCM	Tool Changeout Mechanisms

Application of the Mobile Servicing System to Space Station Maintenance

Abstract

The Mobile Servicing System (MSS) is being developed by Canada to support a number of functions critical to the assembly and operation of Space Station Freedom (SSF), including maintenance of the station and its payloads. In the following subsection of this appendix, the MSS and the elements which comprise it are described. The utilization and features of the MSS for maintenance are addressed, as is the relationship between the MSS and the flight crew, and the MSS and the Flight Telerobotic Servicer (FTS). The MSS provides a capability for automating aspects of its operation which will be of considerable utility in reducing task times and operator workloads. Finally, a number of recommendations are made concerning accommodation of robotics in the SSF design to ensure effective utilization for maintenance.

Description of the MSS

Canada is developing the MSS for SSF to fulfill functions for attached payload servicing, Space Station assembly, spacecraft deployment and retrieval, external transportation, EVA support, and Space Station maintenance.

The MSS comprises five major components, consisting of three flight elements, a set of MSS Control Equipment (MCE), and a ground-based Engineering Support Centre. The three flight elements are the Mobile Servicing Centre (MSC) shown in Figure H3-1, the Special Purpose Dexterous Manipulator (SPDM) shown in Figure H3-2, and an MSS Maintenance Depot (MMD).

The Mobile Servicing Centre

The MSC will serve as a base for robotic and extravehicular crew operations. Mobility of the MSC is provided by the U.S. supplied Mobile Transporter. The MSC will accommodate and transport the Space Station Remote Manipulator System (SSRMS), the Special Purpose Dexterous Manipulator (SPDM), MSC tools, the FTS, the Astronaut Positioning Systems (APS), a Manned Foot Restraint (MFR), up to two payloads or payload ORU pallets, and up to two astronauts.

The Space Station Remote Manipulator System

The MSS includes two manipulator systems. The SPDM will provide capabilities required for dexterous tasks. The SSRMS will perform tasks requiring a long reach or high payload handling capacity. The SSRMS is approximately 17 meters long and will be able to berth a fully loaded Shuttle Orbiter. It is symmetrical in design, with seven rotary joints, and a latching end effector at either end. The SSRMS is designed to operate from Power Data Grapple Fixtures (PDGFs) located on the MSC Base System (MBS) or elsewhere on the Space Station. Its symmetry permits either end to function as the base or the tip, enabling the SSRMS to step between PDGFs–a mobility mode that is called pedipulation.

Each SSRMS latching end effector (LEE) is equipped with a boresight camera. Two additional cameras are mounted on pan-tilt units near the elbow. Data power and video will be passed through the SSRMS to its payloads, thereby enabling other station equipment, including robots, to operate from its tip. Each end of the SSRMS will also incorporate a force torque sensor, from which data will be displayed to the operator and used by the control system to limit the forces and torques applied during operations.

The Special Purpose Dexterous Manipulator (SPDM)

The SPDM has three major segments: a base, a folding body, and a dual manipulator arm assembly. The base is configured with a PDGF at one end and a LEE at the other. This will enable the SPDM to be picked up by the SSRMS, to be transported and positioned at worksites, and will permit the SPDM to attach to grapple fixtures. Where power, data, and video connections are available at a grapple fixture, the SPDM can operate independently of the SSRMS. The base contains one roll joint to enable the SPDM to rotate about its attachment point when operating in the independent mode. There are two latch mechanisms on the SPDM base to which Orbital Replacement Units (ORU) can be attached for temporary storage during maintenance operations.

The SPDM body provides four more degrees of freedom. The tool set will be designed with standard interfaces, compatible with SSF hardware. One face of the upper body will support a mechanism for temporary storage of small ORUs.

The two SPDM manipulators each have seven rotary joints. Each manipulator is approximately 2 meters long, giving the SPDM an overall maximum reach exceeding 5 meters. The manipulators terminate with Tool Changeout Mechanisms (TCMs) which will, in fact, be tools themselves, having latches with which to grasp ORU handles and a rotary tool to actuate ORU retention bolts and latches. Each arm is equipped with a video camera, light, and force moment sensor. A stereo camera pair, mounted between the bases of the arms, will provide wide-angle views of the worksite.

MSS Control

Operator control of the MSS will be provided from the SSF cupola or node workstations. Limited control, primarily for checkout, will be possible from the ground.

MSS as a Maintenance Agent

Many of the features built into MSS have been incorporated expressly to maximize its utility for SSF maintenance.

Mobility

Mobility enables the MSC to travel to the site at which maintenance actions are required. Accommodations on the MSC are provided to permit transportation of other maintenance agents such as the SPDM, FTS, or EVA crew. The two MSC payload ORU accommodations (POAs) on the MSC are provided to permit transportation of other maintenance agents such as the SPDM, FTS, or EVA crew. The two MSC POAs will allow pallets of ORUs or payloads equipped with grapple fixtures to be carried by the MSC for maintenance activities.

The SSRMS is designed to support operation of the dexterous robots from its tip and can position them within a large spatial volume around the MSC and inside the truss. The seven joints of SSRMS will allow the same end effector position to be achieved by many different combinations of joint positions, thereby making it possible to reach around objects that would otherwise block access.

Dexterous Operations

While the SSRMS will provide high loads and torques, and manipulate massive objects with considerable precision, its size limits the range of maintenance tasks which it alone can perform. Dexterous capabilities will be provided by the SPDM. Particular attention has been given to making the SPDM and SSRMS integral and complementary in their operation.

The principle mode of SPDM operation will be from the end of the SSRMS. Local stablization will be achieved by grasping a hardpoint at the worksite with one manipulator while operating with the other, or by attaching the SPDM LEE to a grapple fixture. These approaches impose the minimum design impacts to the worksite hardware. If a grapple fixture local to the worksite privides power, data, and video, the SPDM could be operated from this fixture.

The base of the SPDM is designed to function as an extension to the SSRMS. This will enable the SSRMS to manipulate large payloads using the SPDM LEE while it is holding the SPDM. The SPDM will also be able to operate and perform functions on a payload attached to its LEE while being held by the SSRMS. This will provide particular versatility for installation or removal of large objects. This capability is further enhanced by the ability of the SSRMS and the SPDM to execute simultaneous coordinated motions. Coordinated control will also facilitate access to constrained spaces and will allow repositioning of the SPDM by the SSRMS without needing to detach the SPDM manipulators from the worksite.

ORU Accommodations

The attachment points provided on the SPDM base and the accommodations on the upper body will be used to carry replacement ORUs to the worksite, allow exchange of the failed ORU, and carry it back to the MSC with the SPDM. This will reduce the time required for ORU exchange operations. To enable this feature to be utilized by different ORUs, standard ORU interfaces will need to be developed.

Payloads with compatible interfaces will be able to utilize power, data, and video resources provided by the MSS at the POA, the SSRMS LEE, and the SPDM LEE; they will be able to use power and data at the SPDM TCMs.

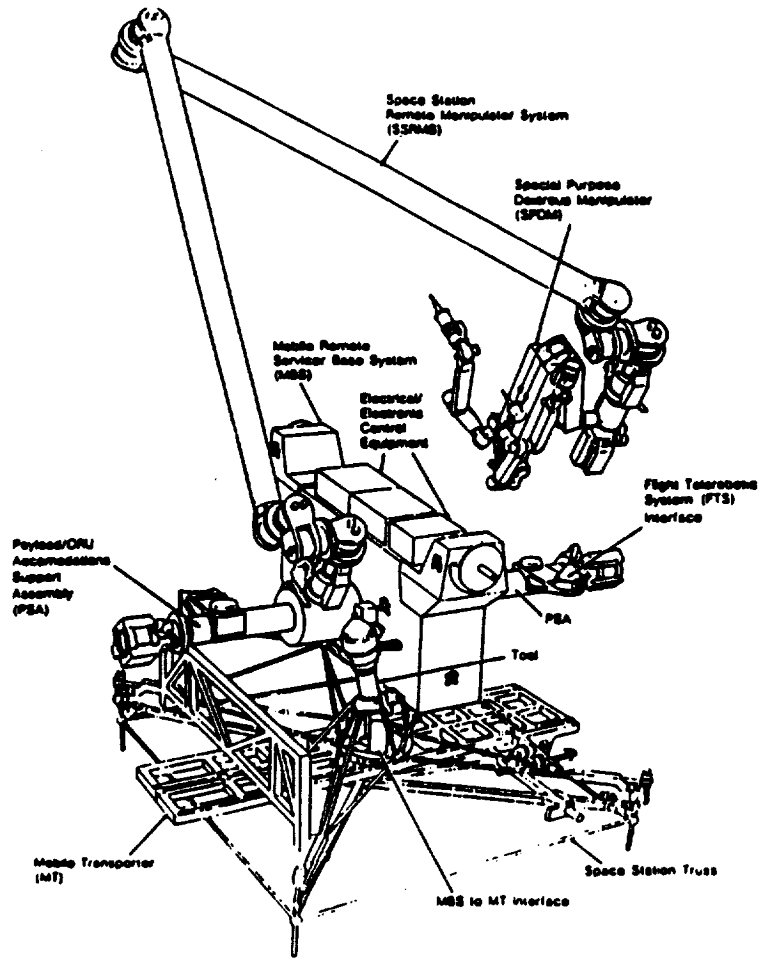

Figure H3-1. Mobile Servicing Center

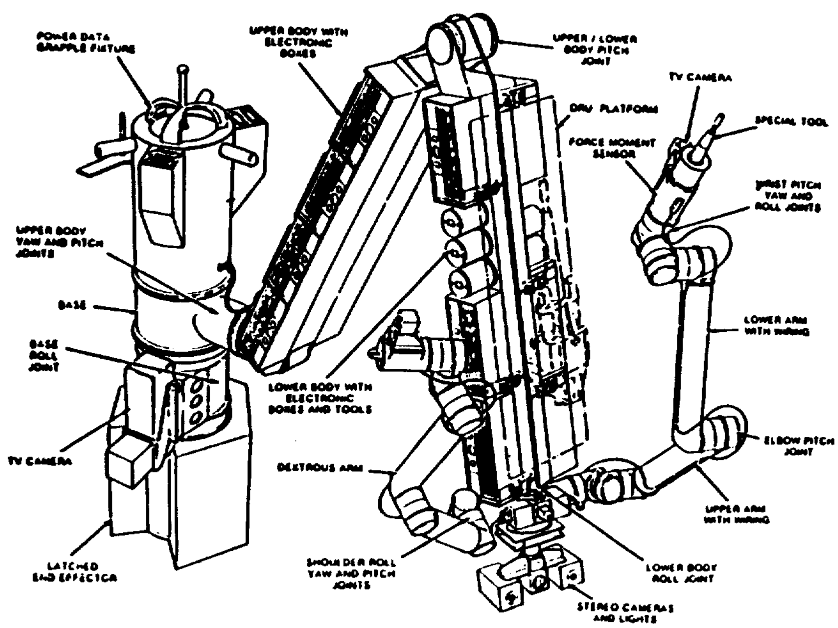

Figure H3-2. Special Purpose Dexterous Manipulator

Tools

The SPDM will have a standard set of four or five tools which it will carry on its upper body. The details of the design and functions of these tools have yet to be determined. So as to be compatible with the broadest set of maintenance tasks possible, the tools will be designed to be compatible with standard station interfaces. Tools for special purpose tasks or non-standard interfaces will be user-supplied.

Since the majority of SPDM tasks are expected to be ORU exchanges, by incorporating in the TCM, the functionality required to grasp ORUs and actuate their release/tie-down mechanisms, one tool can be eliminated, and the mass, volume, and complexity of the equipment at the end of the SPDM arm can be reduced. The same mechanisms which grasp ORUs can be used to grasp tools, and the drive mechanism used to attach/detach ORUs can be used to drive active tools. The TCM concepts have been developed that are compatible with more than one size of ORU interface; however, for maximum utility it is necessary that the potentially large set of different interfaces and attachment mechanisms be constrained by developing program-wide standards.

Control

Both SSRMS and SPDM will be controlled by the same hand controllers and will use the same control modes. This will enable smooth, uninterrupted operation by a single operator from one workstation. Special features will be provided to assist the operator. Closed loop force moment accommodation will be used to control the loads applied, assist with ORU insertion, and other tasks involving contact. A vision system will be able to determine for the operator the position, orientation, and rates of motion of objects relative to the manipulator, and to enable closed-loop vision-based motion. A collision detection system has been developed that would aid the operator in avoiding unwanted contact with local hardware, and would support the planning of tasks. A degree of automated capability will be available to unburden the operators of repetitive or time-consuming aspects of operations. These features will make MSS operations safer and more time-efficient.

Relation of the MSS to the FTS

Support of FTS Operations

The MSC will provide the mobility required by the FTS to transport it to the locality of its worksites. The SSRMS will be used to place FTS at worksites where it can operate independently, or to position it relative to the worksite and allow operation while still attached to the SSRMS.

The MSS will provide power, data, and video services to the FTS for those operations in which the FTS is attached to the MSC. Joint operations of MSS and FTS will be conducted in a serial manner when the two systems are attached, or in parallel if the two robots are being operated independently by different operations in which MSS retrieves and positions ORUs in support of FTS maintenance actions.

Mutual Servicing

The MSS will, where feasible, incorporate standard interfaces and attachment means in its ORUs. A goal of the MSC design has been to make it maintainable by the SPDM. This has been a strong design driver for the SPDM, leading to a very versatile system. Standardization of interfaces will ensure that MSS ORUs are compatible with the FTS tools. The SPDM, in particular, will utilize the FTS as a maintenance provider. Similarly, maintenance needs can be met with the SPDM.

Relation of the MSS to the Flight Crew

The principle objective of the MSS is to extend the capabilities of the flight crew to enable the manipulation and positioning of large masses and to perform tasks remotely which would otherwise require EVA. For maintenance, MSS is a tool intended to make the crew's job safer and simpler.

For tasks where EVA is selected, or required, MSS will be able to assist the crew in a manner similar to that in which the SRMS has positioned objects for the crew to work upon or by providing a base from which to work. Crew memebers will be able to take the place of a dexterous robot at the end of the SSRMS to be positioned for performing external maintenance tasks. A potentially important role of the SSF robots may be to prepare worksites for the crew prior to their egress. This can have significant benefits for reducing the duration of EVAs.

MSS as a Maintenance Requirement

The Mobile Servicing System is a very intricate device having a multitude of moving parts and complex electronic systems. It is required to function in a relatively inhospitable environment for the lifetime of SSF. As a consequence, failures of some of its components are expected to occur.

The critical nature of some of the operations which MSS is required to perform necessitates the incorporation of multiple equipment strings into the design to provide tolerance of failures. This will enable the MSS to be fully functional even if failures have occurred, thereby enhancing safety. The increase in complexity, however, leads to higher maintenance requirements.

As addressed above, the MSS has been designed to be robotically serviceable to the greatest extent possible. The versatility of the SPDM and, in particular, its long reach have been driven by the requirement to service the MSC SPDM, and it may even be able to perform some self-maintenance tasks.

Since the inception of the EMTT study, revisions to the ORU architecture of the MSS have been made with the net effect of substantially decreasing the maintenance time required for MSS. The principle consumer of maintenance resources was originally the thermal coverings on MSC and SPDM. The lifetime of this material is limited by corrosion in low-Earth orbit. The number of thermal blankets has been reduced, and of those that remain, many have been incorporated into the exterior of the ORUs that they cover. For those

ORUs that have a similar mean time between failure to the lifetime of the thermal material, both the ORU and the integral thermal covering will be replaced at the same time. This approach reduces the number of maintenance actions and the maintenance time required because generally ORUs can be replaced more quickly than thermal covers. Further, apparent reduction in the maintenance requirements has resulted from using a definition of maintenance time, which is consistent with that assumed by the EMTT, in place of a definition which included times for other related activites.

As part of the ongoing design process of MSS, means are being explored to make robot-unfriendly ORUs, such as thermal blankets, more amenable to robotic replacement. This should lead to an even higher percentage of MSS maintenance being feasible using the SSF robots.

Automation of MSS Functions

It is recognized that the time of the SSF crew will be a very valuable resource. Reductions of EVA time achieved by use of the MSS as a maintenance agent will result in intravehicular activity (IVA) crew time being required for MSS operation. Accordingly, the MSS is being designed to facilitate the automation of many of its functions, and to enable upgrades to enhance the level of automation over the course of its lifetime. This approach will initially free the crew from involvement in the more mundane and time-consuming aspects of MSS operation and eventually will enable substantial portions of operations to be performed without direct crew intervention.

Automated Operations

Aspects of the baseline MSS operations which will be automated include health and status monitoring; fault detection and isolation to an ORU or redundant path level power-up and power-down sequences; stowing and unstowing of the SSRMS and SPDM; movement of the SSRMS and SPDM following precomputed trajectories; operation of the following precomputed trajectories; operation of the LEEs and the SPDM TCM; SPDM changeout of tools; and capture, maneuvering, positioning, attachment, detachment, and release of ORUs.

The interface between the operator and the robots is very critical in realizing effective control over the functions of the system. Even if a robot's operations can be made fully autonomous, it is not necessarily safe nor desirable to do so. Initially, only very benign aspects of MSS operations would be automated. As confidence in the system is demonstrated, more extensive aspects of tasks can be automated. Not only will operator override always be feasible, but operator involvement in the operation will be maintanined to check status and positioning at the completion of each step prior to proceeding.

Even very constrained use of automated procedures could significantly simplify the execution of teleoperated tasks and decrease task times. For example, robotic positioning and alignment of the tool head over an ORU interface using the MSS vision system will repeatedly save time and reduce operator workload over the course of a single task.

Effective and safe automation of the operations of a system like the MSS in the SSF environment requires flexibilty of the automated system. Ground-base automation frequently takes advantage of the identical nature of repetitive tasks. In an evironment like that of SSF, no two tasks will be exactly the same, even repetitive ones. Unless the robotic system is able to accommodate these differences, the time spent for task planning and setup could exceed the time saved by having a task performed automatically. Automation approaches that rely strictly upon geometric models and interface positions are limited in their flexibility. An approach to automation has been developed for the MSS which could enable very generic task programs to be utilized for different tasks of a similar type. Additionally, the MSS vision system will assist in manipulator positioning using targets, thereby reducing dependence on geometric models.

One growth path which could significantly relieve the demand placed by maintenance upon the SSF crew is to implement control over automated aspects of robot operations from the ground. Major segments of typical maintenance operations, such as power up and power down, or command and control of MT motion, are amenable to this control approach. Aspects of long-duration non-contact tasks such as inspection could also be automated and adapted for ground control.

Resource Requirements to Support Automation

Just as EVA tasks cannot be performed without knowledge of the task and the worksite, similar information is required for tasks to be performed by the SSF robots. If a task is to be performed in a teleoperated fashion, the EVA operator needs to understand the task. If a task is to be performed using the automated capabilities of a robot, information needs to be provided to the robot in a form that it can utilize. The more automated a task is, the more information the robot requires; otherwise the robot will be operating blindly with associated risks.

Achieving safe and flexible automation of more advanced MSS operations requires consolidation of information about the SSF into two databases. One required database is a model of the SSF to support collision avoidance. An ORU database is also required which contains information about ORU location, size, mass, attachment means, removal instructions, location of spares, and other information similar to that which would be required by an astronaut. Neither of these databases contain information that is new. All that is required is that the information be collected and maintained in one place. Both databases could be located on the ground.

Additionally, the other main requirement for automation is computer processing power. Computer requirements are driven not only by the information processing inherent in controlling an automated process, but also by the need to have the operations management and control function of the robot simulate the task immediately prior to performing it. This will ensure that the task can be safely executed.

Test and Verification of Automated Operations

If the MSS is ever to be allowed to execute tasks in a fully automated mode, with less than compete supervision, the functions governing the system control will have to have been fully tested and verified. Full confidence in ground-tested automated operations would also require a high degree of fidelity in the simulation of the environment in which the robot operates. Practical test and verification of automated operations can be accomplished, however, in spite of these limitations.

First, the underlying non-automated system will be fully verified. This will be accomplished in preparation for normal operations and will include the software that controls system operation. Second, automated functions will be developed and demonstrated using a ground-based robot testbed such as the SPDM Ground Testbed. High fidelity systems simulation can then be utilized to test the behavior of the end-to-end system. The MSS Development and Simulation Facility being developed by Canada is integral to the MSS verification process. Finally, automated functions will be flight-tested prior to use.

Automated operation of the MSS is envisioned to be implemented in a phased manner beginning with the most benign functions, such as power up and power down sequences. Non-invasive automated functions, such as collision detection, can be activated and allowed to run in the background during MSS operations to verify functionality and demonstrate usefulness to the operator. Similarly, other automated systems can be activated in an open-loop mode. Data gathered can later be analyzed to verify proper operation of the automated functions.

Once the integrity of automated functions has been tested as described above, then the various primitive automated sequences which comprise more complex tasks can begin to be utilized during on-going operations, beginning with non-contact portions of tasks such as positioning of tools over interfaces. Immediate time savings will be realized. Slightly more sophisticated task elements can then be implemented, such as tool insertion and actuation. When these task elements have been thoroughly tested and used individually for a period of time, they can be linked together to complete larger segments of a task in an automated sequence. With this kind of incremental approach, lower levels of autonomy will be built upon, eventually resulting in substantial time savings and reduced workload for the operator.

Recommendations

It is apparent from the early findings of the EMTT external maintenance study that robotic devices have at least a substantial role to play in the maintenance of SSF. To enable this resource to be used to full advantage, the following recommendations are proposed:

Design For Robotic Compatibility

Current robotics technology is unable to match the dexterity of human beings. Hardware required maintenance should be designed such that it is compatible with the capabilites of the station robots and provide mechanisms which the robots can easily operate and access, including targets compatible with the robot vision systems. This will ensure that maintenance using the robotic systems is feasible and will decrease the time required for maintenance tasks.

Furthermore, to reduce the tool set and the complexity of maintenance operation, designs and interfaces should be made standard across as much of the SSF hardware as can reasonably be accommodated.

This involves some up-front costs; however, substantial long-term savings are to be realized. In fact, if the preliminary findings of the EMTT study are confirmed, designing hardware for compatiblitiy with the station robots could be crucial to ensuring the viability of the Space Station.

Management Processes

The SSF Program involves design and development of hardware by many parties and development of servicing systems by several more. Successful utilization of SSF robots requires strongly supported management initiatives to integrate the robotic systems into the design and development cycle.

Design for Automation

Provision of an appropriate information systems infrastruture will facilitate automated operations of SSF robots. This is analogous to designing hardware to be compatible with the robots. In this instance, the costs to the program are relatively minor, involving the development and maintenance of a number of databases and the provision of additional computers. Not only can immediate savings be realized, but these provisions are fundamental to growth to higher levels of robot system capability.

Preservation of Fisher-Price Database

The ORU database developed through the EMTT study is perhaps the most comprehensive body of information yet assembled defining the SSF ORUs and their maintenance requirements. These kinds of data are fundamental to the development of maintenance task scenarios and procedues and will continue to be useful to the program if maintained. An appropriate group should be assigned the responsibility for continued development and maintenance of this database.

Analysis of Robotic Maintenance Task Timelines

Appendix H4

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Appendix H4

Acronyms List

AC	Assembly Complete
ASPS	Attachment Stabilization and Positioning System
CCTV	Closed Circuit Televisions
CSA	Canadian Space Agency
D & C	Displays and Controls
DMS	Data Management System
DOF	Degrees of Freedom
EE	End Effector
EVA	Extravehicular Activity
EVR	Extravehicular Robotic
FTS	Flight Telerobotic Servicer
GPC	General Purpose Computer
GSFC	Goddard Space Flight Center
HST	Hubble Space Telescope
IEA	Integrated Equipment Assembly
IVA	Intravehicular Activities
JSC	Johnson Space Center
LDEF	Long Duration Exposure Facility
LEE	Latching End Effector
MAGIK	Manipulator Analysis - Graphic, Interactive, Kinematic
MBS	MRS Base System
MPAC	Multipurpose Application Console
MRS	Mobile Remote Servicer
MSC	Mobile Servicing Center
MT	Mobile Transporter
NASREM	NASA/NIST Standard Reference Model
NAT	Node Attachment Tool
ORU	Orbital Replacement Unit
PDGF	Power Data Grapple Fixture
POA	Payload/ORU Accomodation

POR	Point of Resolution
PRLA	Payload Retention Latch Assembly
SAE	Storage Accommodation Equipment
SPDM	Special Purpose Dexterous Manipulator
SSRMS	Space Station Remote Manipulator System
SSF	Space Station Freedom
ULC	Unpressurized Logistics Carrier
UPT	User-Provided Tool
WAF	Worksite Attachment Fitting

Abstract

The primary objective of the robotic external maintenance task team is to initiate an Extravehicular Robotic (EVR) assessment of select Space Station maintenance tasks. This task characterizes how a representative maintenance task might be completed. Assumptions include that each of the tasks is robotically achievable and that the Orbital Replacement Units (ORUs) are robot friendly. Although many Space Station detailed components remain undefined, the most current information on the robots and the ORUs was requested from the technical organizations responsible for their development. Each task was scripted and analyzed, and a timeline was produced. The tasks do not necessarily represent an optimum method to complete the task, or whether the task will ultimately be a robotic task. These timelines, therefore, merely provide insight into how long it will take a robot to do a task according to its specific script and also provide an opportunity to document issues at a detailed level. The shortest execution time that these robotic devices can ever achieve is their design maximum tip velocity. This limit puts a perspective on the timelines. The end-to-end script includes the robot power up, ORU retrieval, translation to the worksite, worksite activities, and, finally, robot power down. The remaining task scripts concern only the worksite activities. The dynamics of the robots; operating constraints such as sun angles and shadowing of equipment; and the power duty cycle of Space Station and the robots are not addressed. Prior to this activity much of the robotic analysis focused on the assembly of Space Station with particular emphasis on the first missions. In analyzing these maintenance tasks and developing end-to-end timelines, the robotic community can now have a programmatic understanding of the issues involved in robotic maintenance on the Space Station.

Introduction

On Space Station Freedom (SSF), there will be three major robotic systems which will aid in the external maintenance program. Those robots include:

FTS - Flight Telerobotic Servicer

MSC - Mobile Servicing Centre
which includes:
MT - Mobile Transporter and
SSRMS - Space Station Remote Manipulator System.

SPDM - Special Purpose Dexterous Manipulator

See Figures H4-1 - 4 for views of these robotic devices. Figure H4-5 shows the relative size and reach of an EVA crew member, the FTS, and the SPDM. The FTS and SPDM are considered dexterous robots due to their ability to perform fine positioning motions (especially in comparison to the SSRMS). They are larger than human size, however, which gives them the positive benefit of relative additional reach capability and the negative effect of being encumbered when moving within the truss and other structure.

The FTS is a Work Package 3 effort at Goddard Space Flight Center (GSFC) with Martin Marietta as the prime contractor. The MT is managed by Work Package 2 and produced by Astro through a subcontract of McDonnell Douglas Space Systems Company. The remaining portion of the MSC and the SPDM are provided by the Canadian Space Agency with SPAR Aerospace Ltd manufacturing them.

The FTS is a dexterous robot capable of handling ORUs up to a maximum of 1200 pounds and a size of 40 inches in any direction. The robot consists of two 7-jointed arms each 80 inches in length and an Attachment Stabilization and Positioning System (ASPS) or "leg" which has 5 joints for a length of 38 inches. The telerobot must have the capability to reach any worksite location within 72 inches of its stabilization point.

The MT is a three degree-of-freedom device which provides mobility along the truss. It can carry the SSRMS, FTS, SPDM, and the ORUs on the Mobile Remote Servicer (MRS) base system. It is capable of translation, rotation, and plane change for the MRS. The Astronaut Positioning System is attached to the MT but was not considered in this analysis.

The SSRMS is a large crane-type central elbow manipulator of 57 feet length with 7 joints and a lift capacity of 255,000 pounds. It will be used primarily to handle large SSF cargo elements. It also serves as a positioning system for the dexterous robots, including the FTS and the SPDM. The SSRMS has a tip positioning accuracy of 1.8 inches and 0.7 degrees. The SSRMS Latching End Effector (LEE) interfaces with a Power Data Grapple Fixture (PDGF) on payloads, ORUs, the FTS, and SPDM.

The SPDM is a dexterous robot which has two 7-jointed arms and is mounted on a 5-jointed articulating platform (body). The SPDM is capable of transporting ORUs attached to its body structure but the attachment interface at this time is undefined. The current handling limits of the SPDM manipulator are 1300 pounds and a size of 39 inches in any direction. The development of the SPDM is to include the capability of doing robotic repair or maintenance of the SSRMS.

The Mobile Remote Servicer Base System (MBS) will have two payload/ORU accomodations consisting of stationary LEEs. The maximum size of the payload/ORU mass is 46,000 pounds, 175 inches in diameter, and 55 feet in length.

These devices will be manipulated by an intravehicular activity (IVA) teleoperator using hand controllers in the Multipurpose Applications Console (MPAC). This control station will exist in the SSF nodes and cupolas.

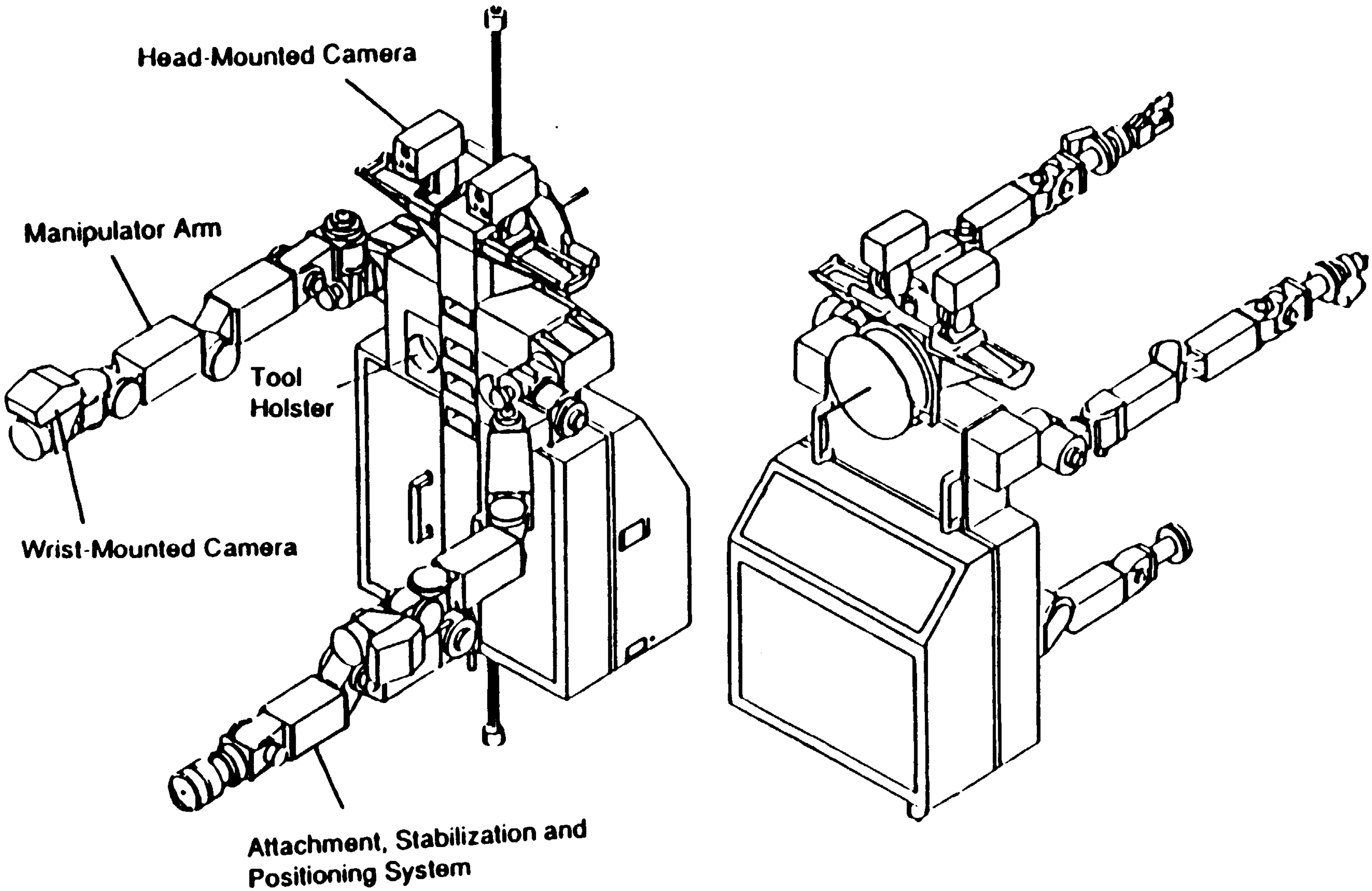


Figure H4-1. Flight Telerobotic Servicer

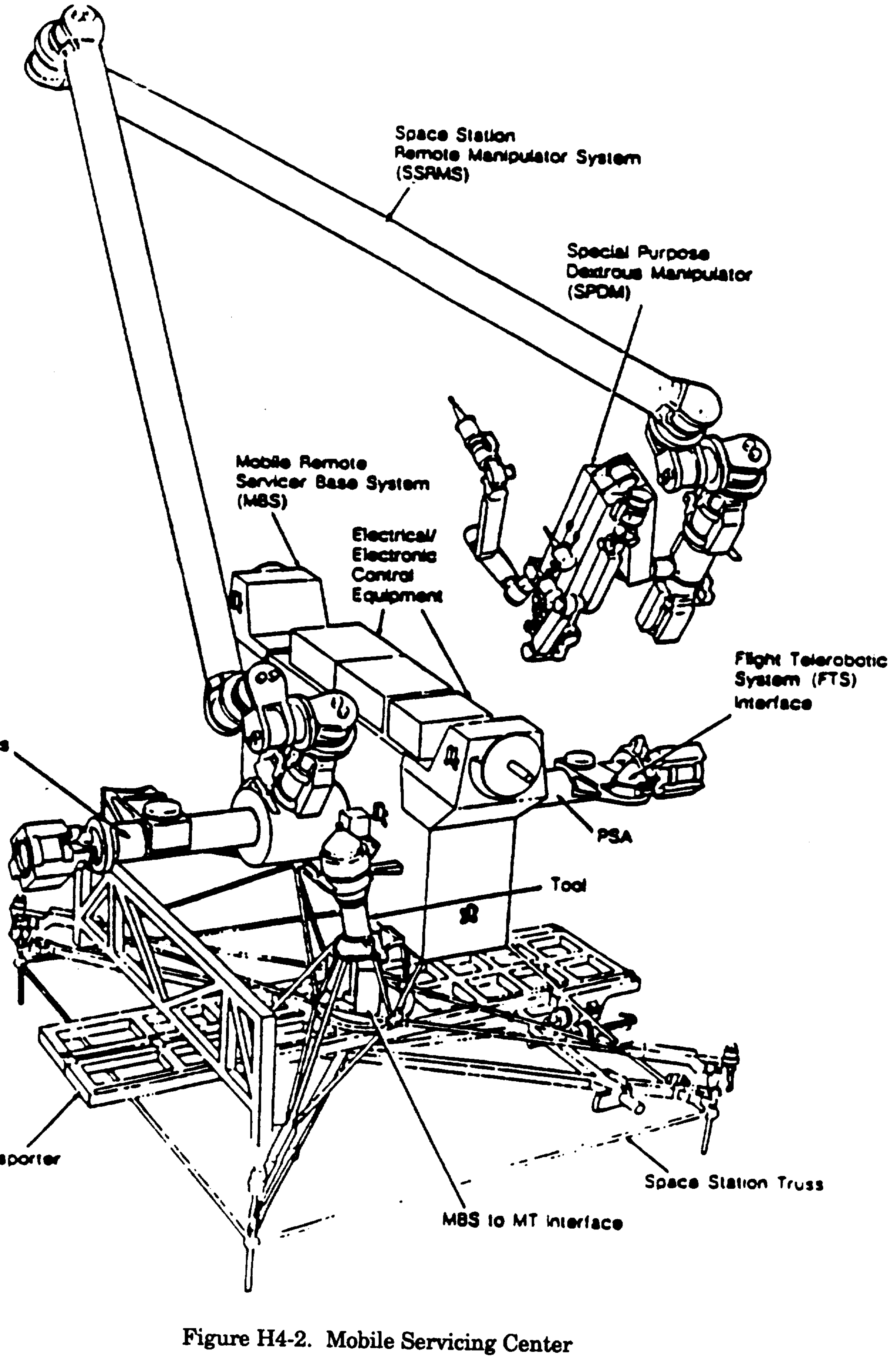
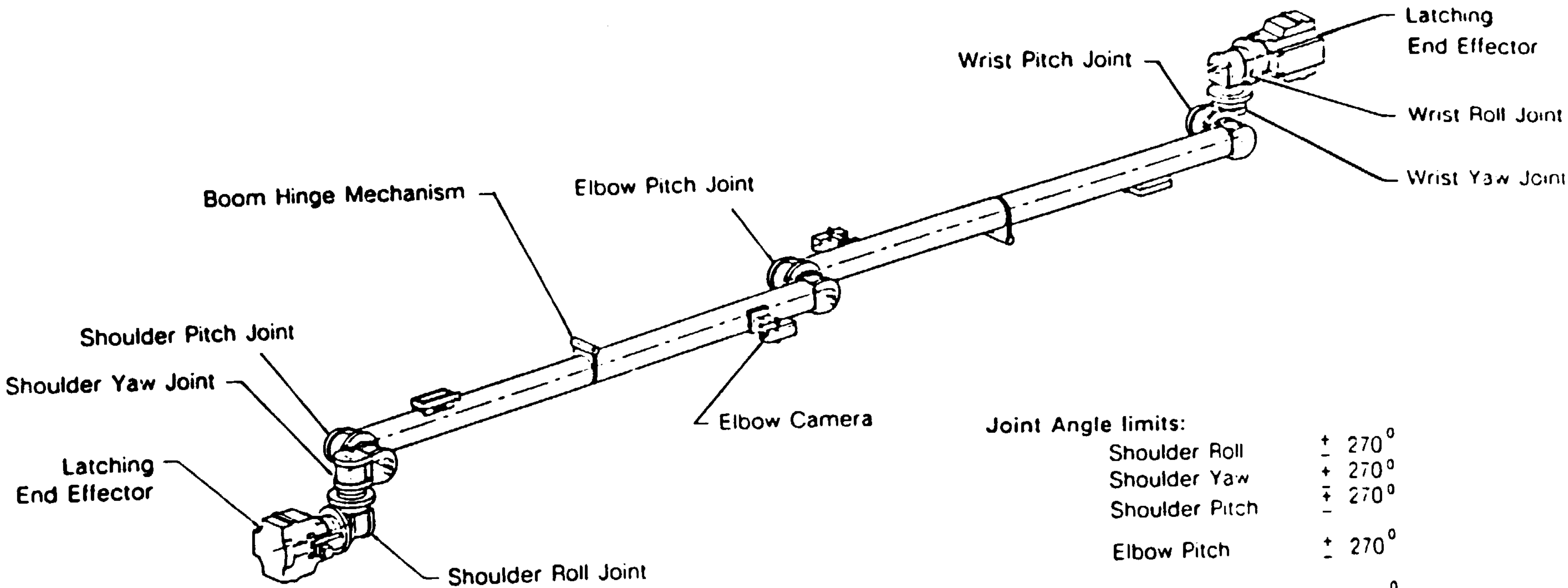


Figure H4-2. Mobile Servicing Center



Joint Angle limits:

Shoulder Roll	$\pm 270^0$
Shoulder Yaw	$\pm 270^0$
Shoulder Pitch	$\pm 270^0$
Elbow Pitch	$\pm 270^0$
Wrist Roll	$\pm 270^0$
Wrist Yaw	$\pm 270^0$
Wrist Pitch	$\pm 270^0$

All Joints Shown in Zero Position

Figure H4-3. Space Station Remote Manipulator System

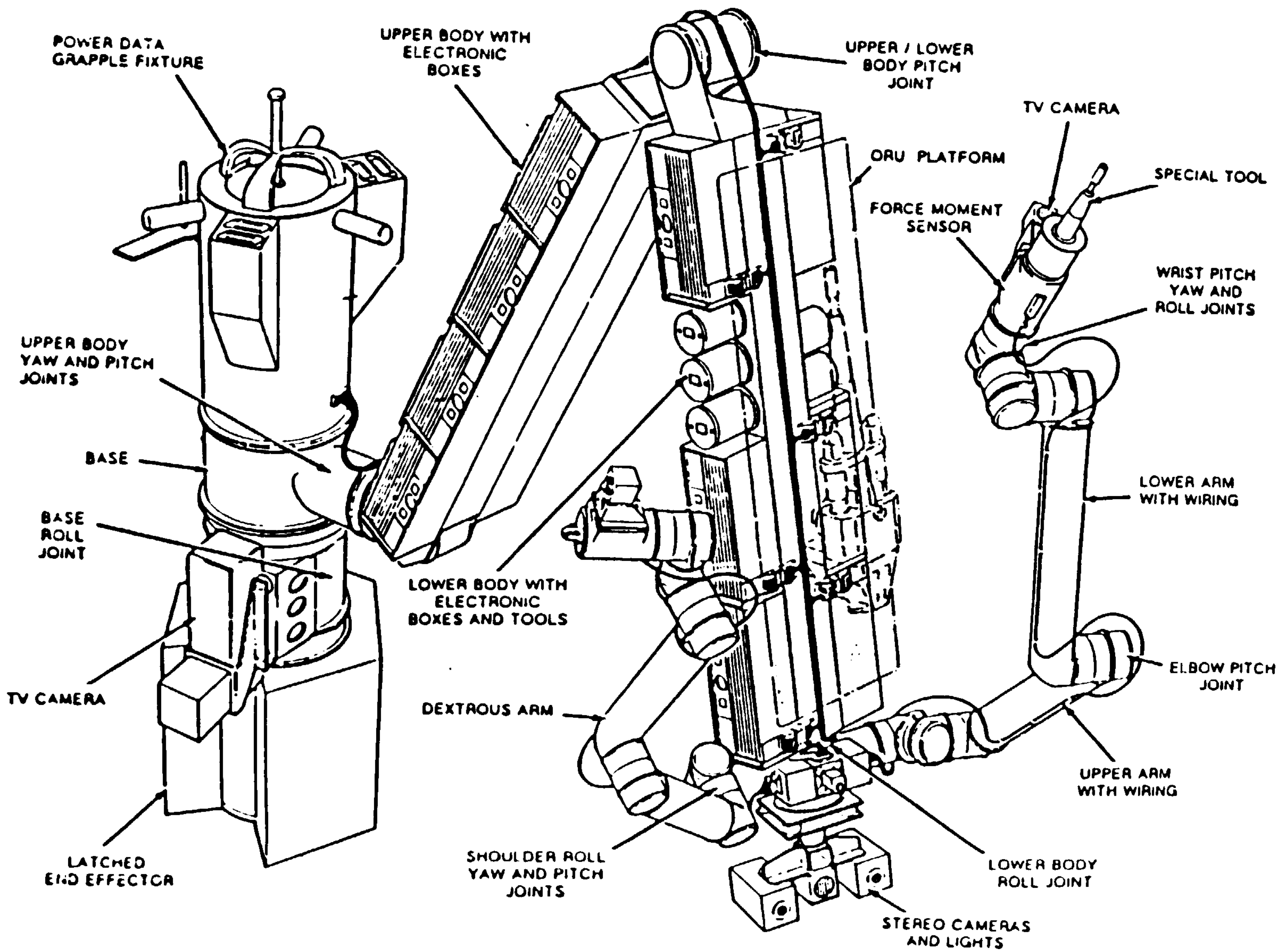


Figure H4-4. Special Purpose Dexterous Manipulator

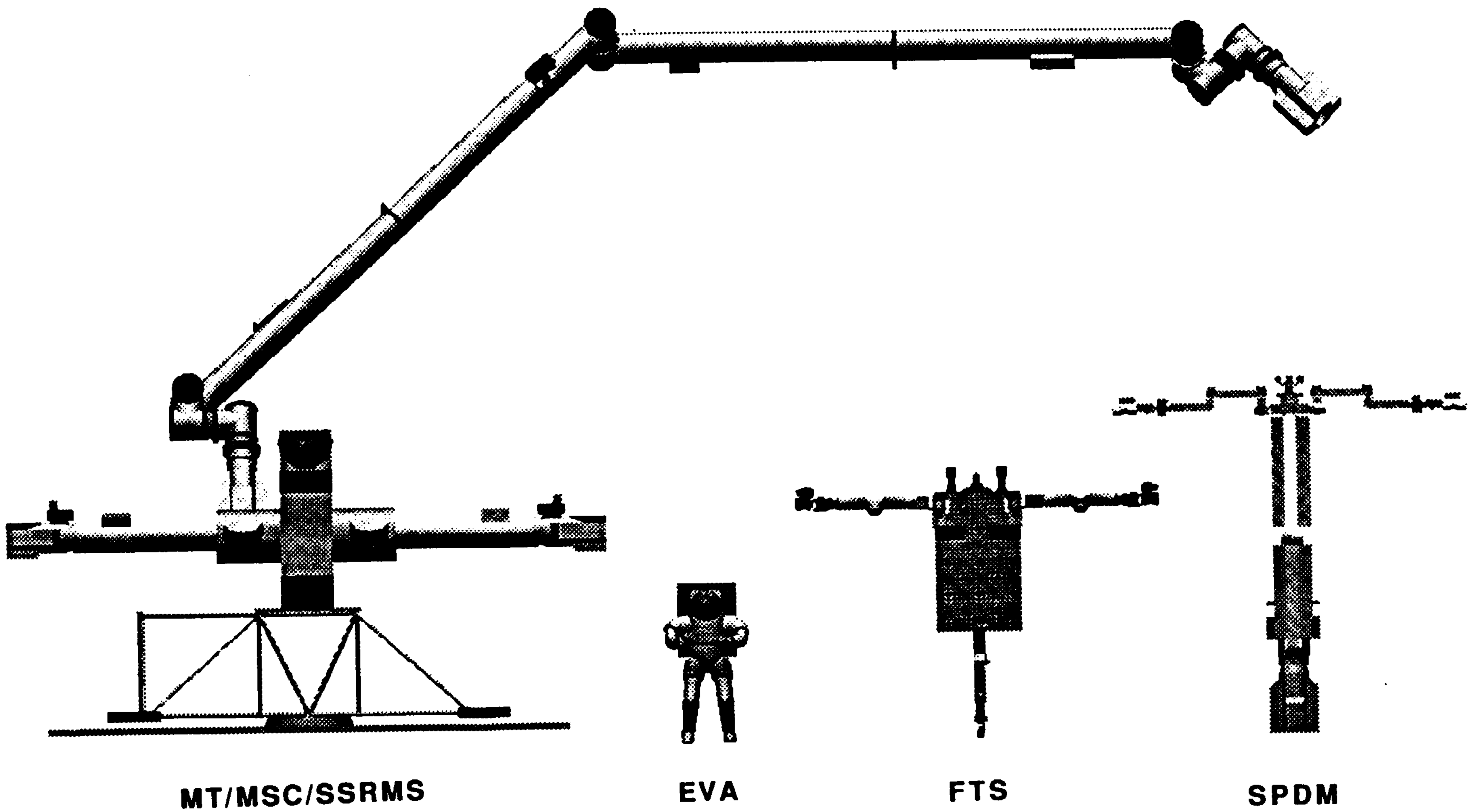


Figure H4-5. Relative Size and Reach of EVA and Robots

Statement of the Problem

1. What is the robotic procedure that is accomplished when completing a select maintenance task (EVR analysis)? Develop an end-to-end procedure to complete the maintenance task. This will be referred to as scripts.
2. What is the time required to complete these maintenance tasks robotically?
3. Identify the requirements and issues associated with this EVR assessment.

Approach

A study was undertaken to understand the scope and breadth of robotic maintenance on SSF. All the functions, elements, and tasks that must be performed or utilized to accomplish a maintenance task were defined and broken into discrete subtasks. Combining the various subtasks enabled any type of maintenance activity to be described methodically and precisely. From this, a Robotic Maintenance Flow Chart (see Results and Discussion Section) was created, and tasks could be defined and end-to-end timelines developed.

A set of representative tasks was developed from the ORU/Maintenance database. The tasks were selected to provide a cross-section examination of tasks from relatively simple to complex, as well as tasks from all work packages. Once the tasks were selected, all of the available information concerning the task was compiled that included any geometric data or existing changeout procedures. However, most of the ORUs were at an immature design stage, which required assumptions to be made concerning ORU design, robot-to-ORU interfaces, ORU-to-station interfaces and changeout procedures.

In developing the tasks, several overriding assumptions were made that set the tone for task development and analysis that carried through the entire Robotic External Maintenance Task study. These assumptions were as follows:

- All tasks are robotically achievable
- All ORUs are robot friendly
- This was not a competition between the FTS and the SPDM
- Both robots have the same capability and tooling to perform the task

Scripts were developed for each candidate task. These detailed scripts began at the worksite and corresponded to Block H in the Robotic Maintenance Flow Chart. Each motion and function of the robotic systems is described in detail and are the basis for the elemental timesteps which make up the composite task timelines.

The simulation tool used for this analysis was MAGIK (Manipulator Analysis - Graphic, Interactive, Kinematic). MAGIK is an engineering analysis environment which allows users to design and interactively simulate manipulator systems. It is the outgrowth of the RMS Planning System (RPS), a Shuttle Remote Manipulator System (SRMS) analysis tool and was developed in the early 1980's.

The primary capabilities and features of MAGIK are

- Validated SRMS flight software
- Analytically validated SSRMS control algorithms

- Man-in-the-loop simulation capabilities
- Parameter-post processing (plotting) capabilities
- Redundant manipulator control system testbed
- Generic manipulator modeling capabilities
- Simulation of the following manipulator systems
  - SRMS
  - SSRMS
  - FTS
  - APS
  - SPDM
  - Japanese Experiment Module Remote Manipulator System

MAGIK was developed because of the need to simulate manipulators and robots in the SSF environment. The SSRMS has been previously modeled, verified and used for Space Station analysis. The FTS was also previously modeled and had been used for some Space Station assembly analysis. Information was provided from SPAR on the SPDM which was then modelled and incorporated into MAGIK.

Once the tasks were developed, a robotics working group was formed to perform the analysis and assess the results. This group included representatives from the Johnson Space Center (JSC), GSFC, Martin Marietta and SPAR. The first meeting was held the week of April 9 - 13, 1990. This meeting provided the first forum where both the FTS and SPDM robotic developers were present and involved in the same task analysis. As a result, a great deal of "cross pollenization" occurred between the two robotic developers and also between the robotic developers and operational users. A consensus was reached as to the process by which analysis should occur in performing robotic maintenance tasks. The existing simulation task models and scripts were modified to incorporate the information provided by the developers.

The maintenance tasks for both the FTS and the SPDM were simulated to perform a kinematic reach and clearance assessment in order to determine if the tasks could be performed robotically. Because of time constraints not all of the proposed tasks could be simulated or timelines developed. However, the process were agreed to by the working group and an estimated end-to-end timeline was developed. This provided the first glimpse of the time required to perform maintenance by robots. These results were presented at the External Maintenance Task Study mid-term review meeting held in April 1990.

During the External Maintenance Task Study mid-term meeting, several splinter sessions were held to discuss the results of the task analysis as well as other topics such as common robotic tools, common ORU interfaces, alignment and vision cues, and SSF robot-friendly design issues.

These topics were followed up with weekly teleconferences to continue the discussion and provide greater depth of understanding of the issues and to discuss additional topics such as collision avoidance and robotic autonomy. The existing tasks were reexamined and modified to incorporate updated operational philosophy and additional hardware information. Additional tasks were included in the analysis matrix to enhance the data set.

A second robotics working group session was held the week of May 29 - June 1, 1990. The purpose of this session was to perform kinematic simulation of the proposed tasks and to develop timelines. The focus of the tasks was split to evaluate performing the tasks telerobotically and semi-automatically. The telerobotic tasks were performed with the Multi-Manipulator Orbiter-Based Crew Workstation, which provides for realistic assessments using hand controllers in an Aft Flight Deck mockup. This mockup includes a 4 X 5 Programmable Display Pushbutton (PDP) pad with menus for the manipulators, robotic mode control, and camera control. A caution and warning system has been implemented which warns the operator when the manipulator is in a singularity or reach limit. The semi-automatic analysis tasks were performed using man-in-the-loop and preprogrammed trajectories to simulate realistic IVA operations.

A video of the IEA/ORU changeout was recorded for documentation purposes. This video illustrates all the activities that must be performed by the various robotic systems. This robotic video corresponds to the EVA IEA/ORU changeout procedures and video. All of the other tasks which were analyzed have video documentation of the worksite task only (Block H).

Results and Discussion

To obtain estimates of the times required for robots to perform maintenance activities, several representative tasks were proposed. These tasks were selected based on complexity factors, information availability, work package inputs, and time availability. The tasks were developed to be as homogeneous as possible with regard to assumptions and modeling fidelity. A common SSF model was developed based upon the Level II Stage Summary Databook, the Assembly Planning Review, and the most current element configurations as defined by the work packages. Figure H4-6 shows the SSF model that was developed for the MAGIK analysis simulation, while Figure H4-7 shows the locations of the Mobile Servicing Center (MSC) utility ports and the major elements of SSF.

A detailed breakdown of all the functions and activities that must occur for robots to perform a maintenance task was developed and is shown in Figure H4-8. This Robotic Maintenance Flow Chart lists all the discrete steps that are necessary from the initial power-up of the robots, to the loading of the robots and the replacement ORU, to the actual replacement of the ORU at the worksite, to the disposal of the ORU, and to the final power-down of the robots.

The focus of the analysis was at the worksite, which corresponds to Block H in the Robotic Maintenance Flow Chart. The worksite tasks were broken into scripts which detailed each step that the robot must perform. The detailed steps were simulated in MAGIK which provided timeline data.

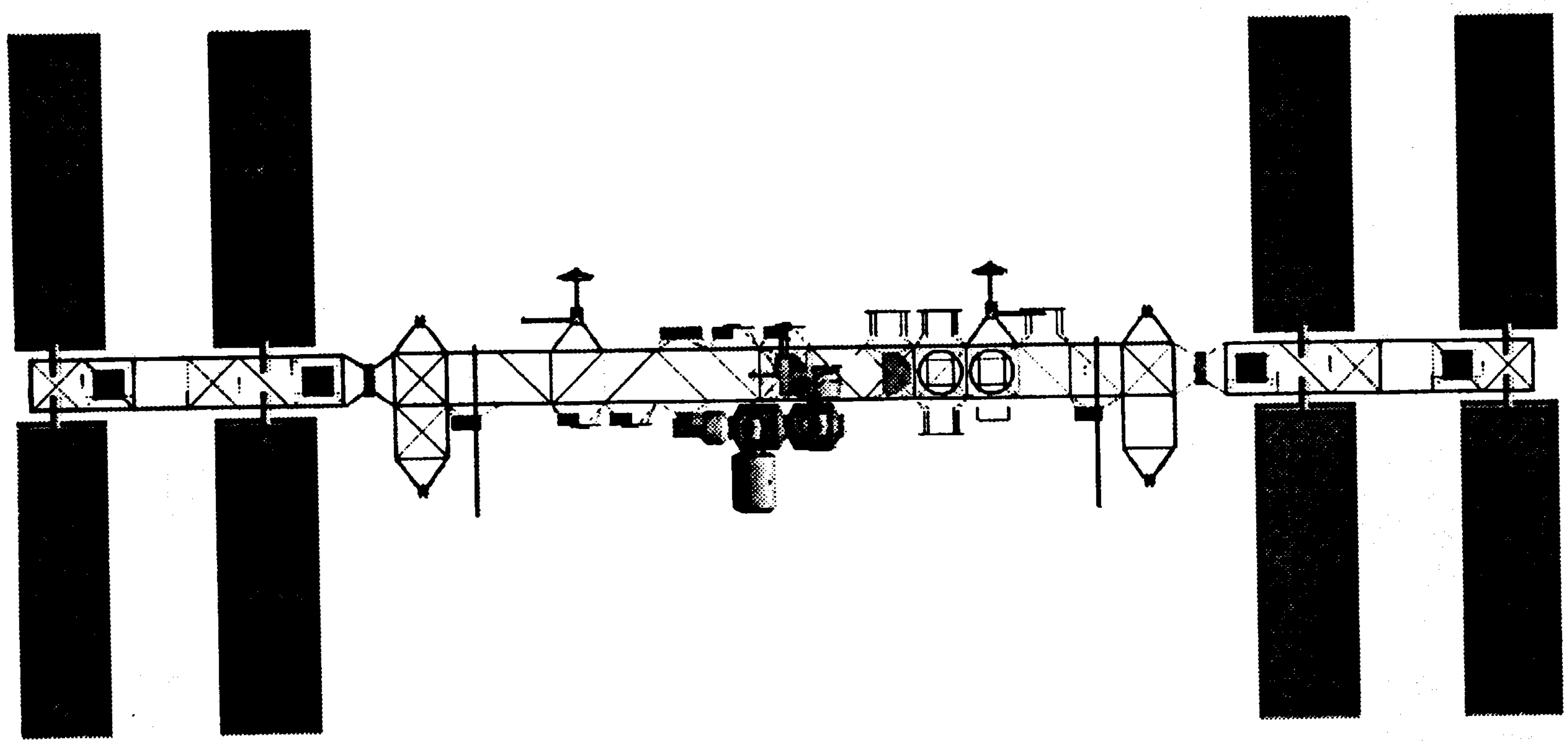
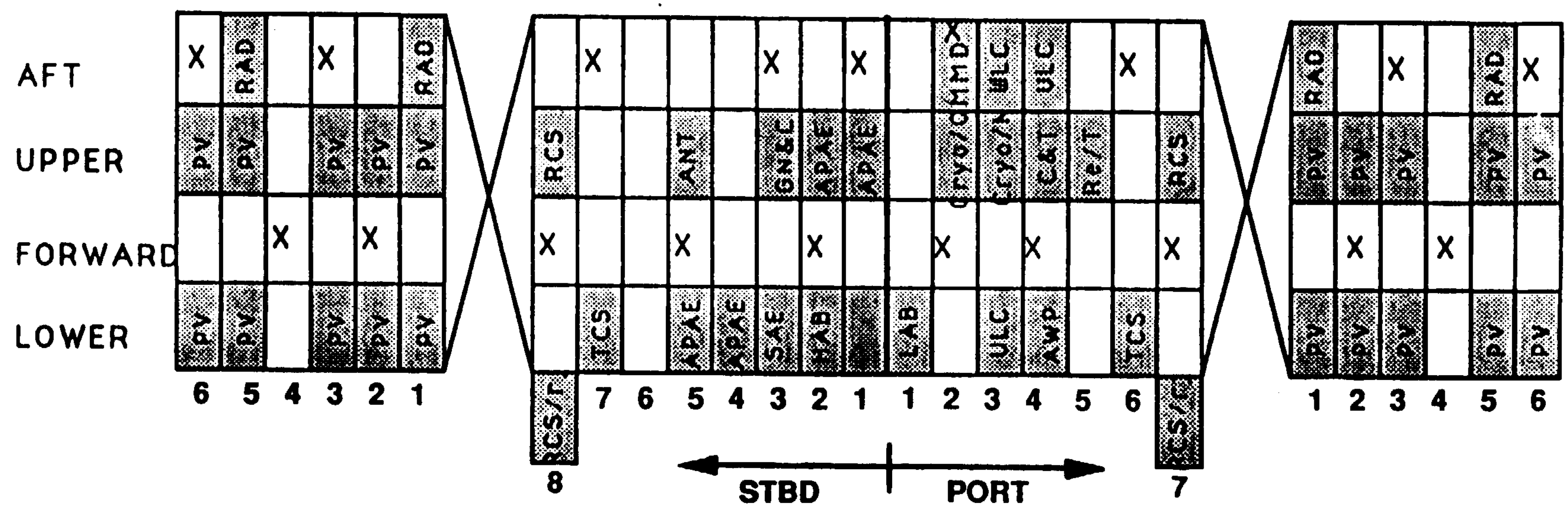


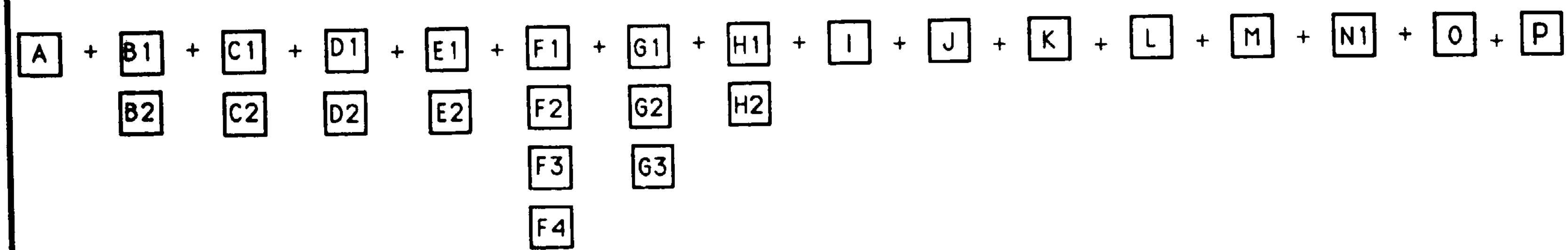
Figure H4-6. Space Station Front View



- **19 Utility Port Positions Identified to Support Assembly, Maintenance and Servicing Operations** (X = Utility Port)
- **Station Configuration drives Location of Ports**

Figure H4-7. MSC Utility Port Locations

ROBOTIC MAINTENANCE FLOW CHART



A - MSC POWER UP
B1- FTS POWER UP
B2- SPDM POWER UP
C1- MSC TRAVERSE/LOAD FTS
C2- MSC TRAVERSE/LOAD SPDM
D1- FTS TOOLS - LOAD
D2- SPDM TOOLS - LOAD
E1- MSC TRAVERSE TO ULC
E2- MSC TRAVERSE TO PALLET
F1- FTS LOADS ORU FROM ULC
F2- SPDM LOADS ORU FROM ULC
F3- SSRMS/FTS LOADS LARGE ORU/PALLET
F4- SSRMS/SPDM LOADS LARGE ORU/PALLET
G1- MSC TRAVERSE BAY
G2- MSC ROTATE
G3- MSC PLANE CHANGE

H1- FTS REMOVE/INSTALL ORU
H2- SPDM REMOVE/INSTALL ORU
I - SYSTEM CHECKOUT - WORKSITE CLEANUP
J - MSC TRAVERSE TO ORU DUMP - SEE G
K - ORU OFFLOAD - SEE F
L1 - MSC TRAVERSE FROM ULC - SEE E
L2- MSC TRAVERSE FROM PALLET - SEE E
M - TOOL STORAGE - SEE D
N - MSC TRAVERSE/UNLOAD ROBOT - SEE C
01- FTS POWER DOWN
02- SPDM POWER DOWN
P - MSC POWER DOWN

Figure H4-8. Robotic Maintenance Flow Chart

Generic Task Assumptions

To perform the tasks it was necessary to make several simplifying assumptions.

Stability and mobility of the robots:

- The dexterous manipulator must be stabilized locally at the worksite.
- If the dexterous manipulator works from the SSRMS, it must stabilize relative motion to a hard point on the worksite.
- If the dexterous manipulator is working independent of the SSRMS at the worksite, then it must stabilize through a berthing mechanism (PDGF, WAF).
- Adequate stability/mobility points exist at the worksite.

ORU manipulation:

- All objects which can be disconnected from SSF must have an interface to the dexterous manipulator which precludes inadvertent release.
- ORU attachment interfaces are common between SSF storage location, interim transit location, and final operational location.
- ORU interfaces to the dexterous manipulators have visual cues to provide for:
  - End effector orientation/alignment to the interfaces
  - Positive verification of end effector grasping and latching
  - ORU orientation and alignment to SSF attachment location
  - Adequate camera views and lighting are provided so as to ensure success (at least two cameras external to the dexterous manipulators)

End-To-End Timeline

During the first robotics group session, an end-to-end timeline was developed of the IEA/ ORU changeout. This was based on previous simulations, agreement of the process and script, and estimated times of the elemental moves as provided by the robot developers. The approach was conservative in nature as to both the estimated times, and in the flow of events, as all of the required steps were performed sequentially. The total time and the subtask breakdown times are shown in Table H4-1. This time represents a first-look realistic estimate of the total time required to perform a robotic maintenance task within the current framework of the SSF robotics and automation program.

The end-to-end timeline provided an opportunity to examine where the major problems existed in utilizing robotics to perform maintenance tasks and where the most effective enhancements could be made to the total robotics system. A time of 13 - 15 hours for IVA operators to be at a workstation performing a maintenance task is an unacceptable time and resource requirement. Several methods were examined to reduce the overall time. These included performing startup procedures in parallel, performing them in an autonomous mode, defining methods of ORU storage and retrieval, defining ORU interface requirements, and using semi-automatic or autonomous functions of the robotic systems. These methods hold promise for reducing times and are being recommended for study in greater detail to more fully understand the requirements on SSF and the robot systems.

A	210	225
B	15	
C	52	221
D	2	
E	9	
F	89	
G	70	
H	180	190
I	(10)	
J	70	221
K	89	
L	9	
M	2	
N	52	
O	(10)	40
P	(30)	

TOTAL = 897 min $\approx$ 15 hrs

RANGE $\approx$ 13 - 15 hrs

TABLE H4-1 - End-to-End Timeline

Task Times

During the second joint robotics group session, the focus of the analysis was to obtain timelines of maintenance tasks in both a teleoperated mode and a semi-automatic mode. The detailed scripts and times are listed in the Detailed Task Scripts and Timelines section while a summary of the task times at the worksite (Block H) is listed in Table H4-2. The time begins once the MSC, robot, and ORU are at the worksite and begin motion to perform the changout. The task time continues until the ORU has been replaced and the robot is stowed on the MSC, ready to return to a home postion. It should be noted that the times represent the fastest that these tasks can be accomplished based on joint rates, simplified models, simplified operational assumptions, ideal environmental conditions, and the immature stage of the ORU designs. They do provide, however, a first-order look of the times required to perform a set of representative tasks.

TABLE H4-2 - Task Summary Table

TASK	FTS (MIN)	SPDM (MIN)	COMMENTS
1) LUMINARE	34	21	SEMI-AUTOMATIC
2) STARTRACKER	27	27	SEMI-AUTOMATIC
3) IEA / ORU	71	60	SEMI-AUTOMATIC
4) TCS MANIFOLD	--	107	SEMI-AUTOMATIC
5) SPDM ORU	14	--	TELEOPERATED
6) BETA GIMBAL	56	62	TELEOPERATED
7) MT BATTERY	26	35	TELEOPERATED

Timeline Comparisons

The analysis was performed in three phases, each with additional analysis maturity and sophistication that was built upon from the previous analysis. The first analysis was the end-to-end timeline of the IEA/ORU changeout that was produced using estimated times by the robot developers. It was conservative in nature and served as the starting point in determining the direction that the follow-up analysis should take. The second phase provided timeline analysis that was obtained from teleoperation simulations. The third phase examined additional tasks that were analyzed using semi-automatic functions. The common link between the analysis methologies was the IEA/ORU changeout that was performed by the FTS. The results in Table H4-3 show the difference between the three methods performing the same task. This task can also be compared to the EVA timeline of IEA/ORU changeout.

TABLE H4-3 - Timeline Methodology Comparisons

TASK	METHODOLOGY	TIME (min)
1) IEA/ORU CHANGEOUT	ESTIMATED	190
2) IEA/ORU CHANGEOUT	TELEOPERATED	201
3) IEA/OUR CHANGEOUT	SEMI-AUTOMATIC	71

Multiple ORU Task Times

The timelines that were produced in this analysis concerned changing out a single ORU per task. A more resonable assumption to make about on-orbit maintenance would be that multiple ORUs would be replaced per maintenance exercise whenever possible to increase overall efficiency. Extrapolating the teleoperation data of the IEA/ORU changeout provides some information on scaling efficiencies. Table H4-4 lists the results of changing out multiple ORUs and shows the worksite time (Block H), the total end-to-end time (estimated) and the percentage difference increase in time

TABLE H4-4 - Multiple ORU Task Times

NUMBER OF ORUs	TASK TIME(min)	TOTAL TIME(min)	% DIFF OF TOTAL
1 ORU	201	917	0
2 ORU	381	1098	19.7
4 ORU	744	1460	59.2

Simulation Versus On-Orbit Experience

The most recent analysis of these tasks using semi-automatic functions shows that the task times are quite good. Both the FTS and SPDM were able to perform the tasks and do so in an acceptable time. However, it must be noted that these simulations were made under ideal conditions with several simplifying assumptions. As the designs of the Space Station and ORUs mature, the tasks will increase in complexity and, therefore, time. Also, current SRMS simulation planning times vary from actual on-orbit experience. As an example:

STS-31 HST Deploy (SRMS operator - Steve Hawley)

Unberthing to low hover	Planned 10 minutes Actual 20 minutes
Overall manipulator timeline	Planned 45 minutes Actual 50 minutes

STS-32 LDEF Retrieval (SRMS operator - Bonnie Dunbar)

Low hover to PRLA indication	Planned 35 minutes Actual 60 minutes

The preceding examples were well-known tasks and were extensively trained tasks that were performed with experienced operators using a manipulator system that has been used for years. The procedures and timelines were developed long before the mission occurred, giving ample time for training and procedures development and verification. The actual times, however, were longer than predicted due to normal human on-orbit caution in performing tasks and the ever-present K factor.

The maintenance tasks were also simulated using unloaded-joint rates. There will be an increase in times when the data is available to permit analysis with loaded-joint rates. If the tasks are to be performed in a teleoperated mode as opposed to a semi-automatic mode the time will also increase due to operational constraints and procedures. The following analysis times were taken from an assembly assessment showing the difference in time between unloaded, loaded and operational constraints using the SRMS. The unloaded and loaded times were taken from MAGIK simulations while the operations time was an estimate based on past flight logs and included such items as manipulator dynamics damping, changing camera views, operator pause points, checklist actions, and other standard telerobot operations.

PAYLOAD	UNLOADED	LOADED	OPERATONS
IEA (32K IBS)	2:00 MIN	11:30 MIN	34:00 MIN
FTS (1.5K LBS)	4:00 MIN	11:00 MIN	19:00 MIN
SAE (0.5K LBS)	4:30 MIN	7:00 MIN	20:00 MIN

There are other factors which influence the total time that a task requires for completion. These include the damping time required when moving a large manipulator like the SRMS due to the flex in the long boom segments, the dynamics of arms and servos, load-limit factors, runaway stopping distances, and other operational and safety constraints. These and others can all have an influence on task time and must be considered on a task-by-task basis.

Teleoperations Versus Semi-Automatic Control

Current manipulators that are used in space (i.e., SRMS) are operated in a teleoperations mode. The operator is present in the Aft Flight Deck Control Station and controls the SRMS by using hand controllers. Operation of the SRMS is based on a man-in-the-loop concept. The SRMS is controlled by the operator who makes command inputs based on visual, out-the-window views and feedback information from the Closed Circuit Television (CCTV) and information available from the Displays and Controls (D&C) panel.

There are two types of automatic control modes available to the SRMS. One type is a group of auto sequences that become part of the SRMS software prior to launch. On orbit, the General Purpose Comptuer (GPC) will maneuver the arm through the auto sequence selected by the SRMS operator until a final position and attitude are reached by the SRMS. This requires extensive preflight planning and does not take into account any changes that may occur during the flight. The second mode is initiated on orbit. The SRMS operator can maneuver the arm from its existing position and attitude to a desired position by entering the data into the GPC via the computer keyboard. Neither mode has collision avoidance or detection capabilities.

These modes have been used on previous flights, such as the LDEF retreival, where a series of auto-sequence maneuvers were used to perform a photo survey. Most maneuvers of the SRMS, however, are performed manually in the teleoperation mode. This includes berthing and unberthing and moving the arm/payload around in the Orbitor payload bay. As stated earlier, even with extensive preflight planning and training, teleoperations with the SRMS generally take longer than anticipated.

The end-to-end timeline that was developed was based on performing the maintenance tasks in a fully teleoperated mode. This produced a time that was unacceptable as a resource drain on IVA and SSF operations. This led the robotic task team to investigate methods for automating the robotic systems. One method was to examine the effects of increasing the automatic functions of the robots versus performing all operations in a teleoperation mode.

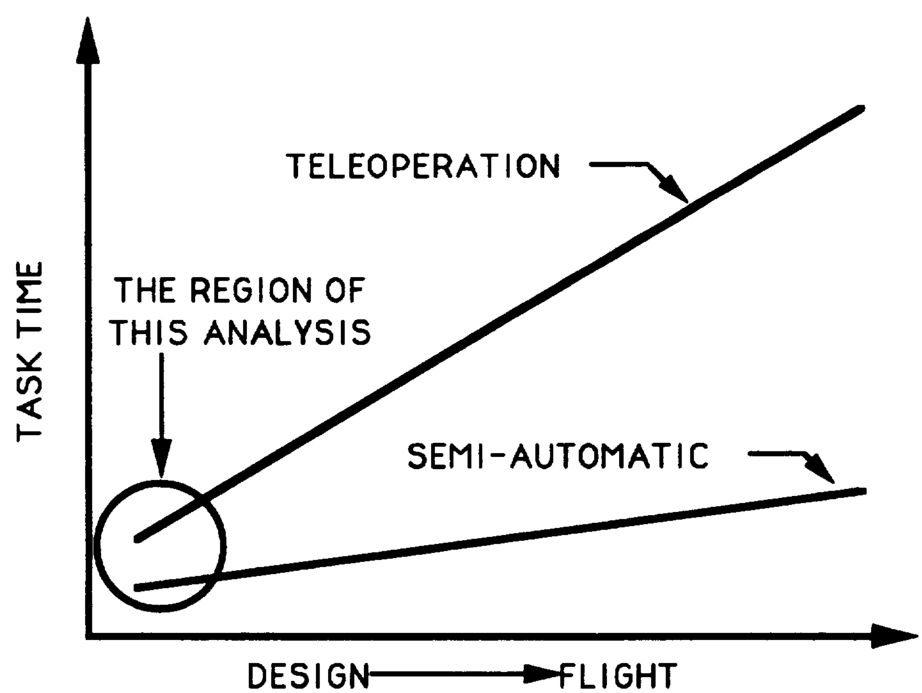
As the maintenance tasks were being developed, the analyst would perform a series of trajectories in teleoperation mode that would place the robot/manipulator in the correct position and attitude. These trajectories were recorded and stored in the computer. When the task was being simulated for timelining, the auto-trajectories were recalled and used for all motions except for grappling, which was performed manually. This type of robotic control is termed semi-automatic in this report because most of the motion is controlled by the robot and merely monitored by the operator. This type of control is sometimes referred to as supervised autonomy; however, that would be a misnomer in this case, since the robots make no decisions based on sensing data and only perform preprogrammed manuevers in most cases.

The analysis indicates that performing robotic tasks semi-automatically will reduce the time required for task completion. The simulation was designed to be an extrapolation of current robotic autonomy capability. Existing industrial robots can use this type of control within a stable and known environment. Current space manipulators have this capability in a limited form, although it has not been utilized extensively. With the increased precision, reliabilty, computing power, and operational experience that the SSRMS, FTS, and SPDM will offer, semi-automatic control should be fully utilized at Assembly Complete (AC).

Using semi-automatic functions, once reliability and confidence have been established, will enable tasks to be performed faster than by humans using telerobotic control only. This speed difference will become greater as the complexity of the task increases. As more is known about a task, such as when the design matures, the more complex it becomes and the longer it will take to perform the task. The more manuevers and functions that must be performed places an ever-increasing workload on the operator. Table H4-5 illustrates this point. The slope of the teleoperated task should increase at a greater rate than the semi-automatic task, indicating the performance differentiation as task complexity increases.

A simular concern exists for training. Current SRMS tasks require extensive ground training which includes computer simulations, 1-g hardware trainers, and Weightless Environment Test Facility (WETF) sessions. Many man-hours of training occur before any task is performed with the SRMS and every move is planned in exacting detail. On-board the Space Station this training philosophy must necessarily be changed due to the limited crewtime resource availability and the limited amount of training facilities that will be available on orbit. With crews spending six months or more on-orbit, it will be impossible to train for every type of maintenance task that will occur, or to train in such thorough detail as is now done. This inadequency of training capability also leads to the requirement of having semi-automatic control functions on the robotic systems. The robots themselves can be trained from the ground where there are available facilities and time, freeing the crew to performing the Space Station's primary missions.

TABLE H4-5 - Teleoperation Versus Semi-Automatic Task Times



Discussion

During the course of the robotic maintenance study, many issues were raised, recommendations offered, and observations given by all of the participants. The following is a non-prioritized compilation of these results.

Worksite Design

- Every worksite where ORUs will be serviced by a telerobotic system must be designed to be serviced by a telerobotic system.
- All telerobotically serviced worksites must be easily accessed by the telerobot (e.g., debris shields covering ORUs must be designed to facilitate easy access to the ORUs they cover).
- Robotic tasks should be designed for service by both telerobotic systems; FTS & SPDM.
- Tasks performed in the vicinity of the radiator may have a problem with thermal radiation and absorption, independent of the maintenance service provider (EVA or EVR).
- FTS assumes Worksite Attachment Fittings (WAFs) will be located at worksites, but the number, location and the utility of using WAFs at any given worksite is undetermined.
- There is a requirement for additional cameras and lights in addition to those provided by the robots. Each worksite will have varying requirements.

ORU Design

- The number of ORU types must be minimized to aide in the required training and tooling needed for maintenance tasks. As the type of ORUs are minimized, the robotic time required to complete a task will decrease because the IVA operator will have a greater efficiency because of simularity between tasks. Another benefit also includes the decrease in the amount of variety of training.
- The targeting/alignment aides used to handle ORUs needs enhancement. This could be accomplished through bore-sighted cameras through the end effector.
- ORUs can be stored on a ULC attached to the MRS at the POA. A ULC can be retrieved and stored by the SSRMS only, eliminating the need to operate the dexterous manipulators for ORU retrieval before arriving at the worksite. This could save a substantial amount of time.
- ORUs require some type of carrier mechanism while they are being transported on the MSC.
- The depth of the ORU should be a maximum of 30 inches to allow the robot to remove the ORU without being repositioned by the SSRMS (especially if one dexterous arm is stabilizing).
- ORUs should be
  - self-aligning
  - have soft-dock capability for initial attachment
  - positive lock mechanism with indicator
  - attachment bolts should be fully drivable through entire thread length and not require togglingbetween bollts for ORU hard dock alignnment

Robot Tooling

- All dexterous robotic system tools should be functionally identical to facilitate ORU commonality.
- No telerobotic task should require more that two tools.
- The Module Servicing Tool (MST) is not robotically friendly because of its long snout length.
- There are currently no identified tools or sensors in the Space Station Program, other than CCTV, for robots to perform inspection tasks.

Robotic Design

- SPDM arm shoulder joint #1's zero position needs to be adjusted such that it places the arm directly overhead.
- The FTS ASPS should be lengthened and increased to no less than 6 DOF.
- The FTS ASPS should have the ability to wield a grasping type tool.
- A camera should be added to the FTS ASPS.
- The FTS needs the capability to stow small ORUs on its body to minimize trips between the MSC and worksite. Drivers for this requirement include time, safety, and power consumption.
- Seven DOF control of the FTS arms is a preferred operations mode.
- Both the FTS and SPDM arms should increase the wrist pitch and wrist yaw joint travel limits to +/- 120 degrees.
- FTS ASPS shoulder pitch needs greater than +/- 90 degrees.
- The requirements (hardware/software) for a WAF-to-PDGF interface element need to be identified.

Unknowns/Questions

The following area is provided to amplify areas concerning the design and operational philosophy of the Space Station that will affect these timeline analyses. Many of the concerns are currently being addressed with respect to the preliminary design configuration of the Space Station.

- How long can the MT be used before it needs to be recharged?
- What does the ORU carrier on the MSC look like? Does a drawer of the ULC travel on the MSC or just the specific replacement ORU? Commonality should exist between the ORU interface with the ULC, the carrier on the MSC, and SSF.
- What are the thermal constraints of these robotic devices and how do these impact timelines?
- Are diagonal truss members removable to complete maintenance tasks? This could add maneuverability of the robots within the truss structure.
- What are the keep-alive requirements for the ORUs?

- What are the requirements concerning robots working close to a structure such as the truss? Runaway concerns exist for all the robots but especially for the large SSRMS manipulator.
- What are the other robotic maintenance discriminators (besides time) that are drivers, such as other allocated resources (power, thermal, etc)?
- Since neither the FTS or SPDM have independent mobility, they are dependent on the MSC which in turn drives all maintenance philosophy and places greater emphasis on MSC reliabilty.
- Total robotic systems reliability and on-orbit maintainability requirements need to be studied.
- The overall logistic/robotic/maintenance philosophy and architecture must be studied to obtain a greater efficiency of the system.
- There is a need to reassess these tasks with realistic lighting constraints. The mean time between failures of the lights and cameras will be critical. These pieces of equipment are extremely essential for robotic maintenance tasks. Concern exists that these devices have a history of high failure rates.

Recommendations

A number of recommendations made by the participants of the robotic external maintenance task team are contained in this section.

From this analysis, it has been determined that the robotic devices will need to have some semi-automatic functions and, therefore, not be competely teleoperated. Some basic functions were explored at the final meeting which include automatic sequence points. It will also be necessary to incorporate the automated functions in routine common maintenance activities and have them become an accepted mode of operation for the robots. The FTS project has been incorporating the NASA/NIST Standard Reference Model architecture which can lend itself to automating the robot. The SSRMS and SPDM project are also looking at methods to automate their systems. It should be noted that total robotic autonomy without a robot friendly Space Station will not solve the problem of the number of required maintenance hours.

Efforts need to continue in developing the requirements for element-to-robot compatibility. Specific questions about the robot-to-ORU interface, ORU-to-Space Station interface, alignment guides, and visual cues, were raised and had to be addressed to analyze each task. It became evident from this work that Space Station should minimize the number and type of interfaces and tools required. It was recognized that these tools will have to be duplicated for the EVA crew member, FTS, and SPDM. No task should be limited to a specific robot or to only an EVA crew member. A specific example of an item that is not robot friendly is the maintenance of thermal blankets. Also, although Work Package 4 has been conscientious of robotic maintainability in its design, the tasks become extremely difficult because the equipment is located inside the truss structure. Accessibility to the worksite is imperative.

Much more work is necessary to integrate the different robotic systems. To help facilitate the speed of operations, it will be necessary to automate some repeatable functions such as the SSRMS grappling the FTS or the SPDM. There should be more focus on automating the system checkout with integrated software. The robot developers have automated their system checkout, but they have not addressed it from an integrated system perspective.

Ground control of robots is necessary to eliminate the high amount of IVA crew member time and has been strongly overlooked to date. The automatic functions could be the first portion of the work load that could be transferred to the ground. For example, the translation of the Mobile Transporter along the truss should not require the dedicated attention of the IVA crew member. This task could be automated with supervised ground control. Inspection tasks are also well suited to ground control. The hooks and scars for these systems need to exist especially in the DMS and communication systems.

Another area which should be analyzed is the Space Station Logistics. This work brought up questions concerning how the ULC is used and configured. Will there be dedicated ULC to replacement ORUs and another ULC for expended ORUs? This analysis focused primarily on one task at a time; additional work needs to determine how to do multiple tasks. Other areas that require further analysis are robots working together to do the maintenance task and the EVA crew member and the robots working together.

Concluding Remarks

This work has greatly expanded the knowledge base of the robotic capabilities and their roles in performing external maintenance on SSF. Limited knowledge of the FTS and its operations existed, but its primary focus had been on early assembly missions. Until the meeting in April, not much information was known about the SPDM beyond the oblique view illustrated in Figure H4-4. Previously, each robot designer would separately provide function and interface information about his or her devices. The robotic community has begun to learn about each of the systems and their operational capabilities. Now, task analysis has begun with the preliminary information obtained to date, focusing on integrating the robots into SSF. This analysis should not cease. This effort has provided a strong focal point of the external maintenance robotic task analysis. All of the robotic participants agreed that these meetings were beneficial in exchanging information. A common recommendation is that a forum similar to the Assembly Planning Review should be estabilished to continue to work these issues.

Another goal should be that each of the robotic devices can assist the other in self-maintenance. Also, robotic reliability should be addressed with trade studies being completed that address how often robots are down for their own maintenance.

With the completion of these scripts, a robotic choreography and timeline methodology has been developed by the robotic task team. The development of a common robotic language such as the Task Analysis Methodology verbiage is beneficial, especially when developing scripts of various tasks for multiple manipulators. Now, the robotic community can address methods and required time for some representative maintenance tasks.

Detailed Task Scripts and Timelines

This section is divided into three parts. The first part provides some background information concerning the tasks and analysis. The second part contains the end-to-end script and timeline for the FTS IEA/ORU changeout, while the third part contains all the detailed task scripts and timelines that were analyzed.

Part One

MAGIK Parameters

The analyses and timelines generated by the simulation tool MAGIK are dependent upon the specific configurations of the tool. These analyses and timelines are also dependent on the configuration of the manipulator systems in question. The control algorithms utilized by MAGIK were manipulator specific. The SSRMS was controlled using the proposed SPAR rate law with the Shoulder Roll/Shoulder Yaw (SR/SY) Auto and Joint Limit Avoidance objective functions. The dexterous manipulators were controlled using the SPAR rate law with the Potential Energy and Joint Limit Avoidance objective functions. These control laws and objective functions are documented in the "SPAR Presentation to the Mobile Servicing Center Working Group Meeting, #4," January 26-27, 1989, and in McDonnell Douglas Transmittal Memos TM-A03-4203 and TM-A03-4204.

The manipulator parameters used for the study include joint angular rate limits, joint travel limits, end effector translational rate limits, and end effector rotational rate limits. In semi-automatic operation values for these four parameters types were derived from the SRMS and applied to all the manipulators with the exception of the joint travel limits which are manipulator specific. Joint angular rates used were 2.29°/sec for joints #1 and #2, 3.21°/sec for joint #3, and 4.76°/sec for all others. End effector rate limits of 2 feet/sec and 4.76°/sec were also applied to all manipulators. With the teleoperated simulation, the SPDM arms, SPDM body and the FTS arms have 5°/sec for joint and end effector rotational rate limits, and a translational rate limit of 2 feet/sec. The constraints on the SSRMS are 4°/sec for the joint and end effector rotational rate limits and a translational rate limit is 1.2 ft/sec.

Manipulator joint travel limits in both the semi-automatic and teleoperated simulations appear in the following table.

Table H4-6 Manipulator Joint Travel Limits

Manipulator	Jnt 1	Jnt 2	Jnt 3	Jnt 4	Jnt 5	Jnt 6	Jnt 7
SSRMS	+/- 270°	+/- 270°	+/- 270°	+/- 270°	+/- 270°	+/- 270°	+/- 270°
FTS ASPS	+/- 135°	+/- 90°	0° to 180°	0° to 90°	0° to 180°	N/A	N/A
FTS ARMS	-180° to 0°	-225° to 90°	-90° to 120°	-180° to 0°	+/- 90°	+/- 90°	+/- 180°
SPDM BASE	+/- 240°	+/- 240°	-180° to 0°	0° to 270°	+/- 240°	N/A	N/A
SPDM ARMS	+/- 180°	+/-180°	+/-180°	+/-180°	+/- 90°	+/- 90°	+/- 360°

All manipulators were driven at maximum rates regardless of payload mass properties. All auto-sequences produced during execution of these analysis were hybrid sequences utilizing standard orbiter-type Point of Resolution (POR) auto-sequence points as well as joint angle trajectories. These joint angle trajectories are linearly interpolated between angle sets.

When analyzing these tasks, various control algorithms of the FTS were evaluated. In the semi-automatic maintenance tasks, the FTS was modeled with the same 7 DOF control algorithm as applied in the SSRMS and SPDM. This provided an opportunity to evaluate the evolutionary methods of control with the FTS while the teleoperations tasks used the current projected control method of indexing the shoulder roll joint and 6 DOF control of the remaining joints on the FTS arms. To provide a consistent basis of comparison, the IEA/ORU task, completed both semi-automatically and teleoperated, used the 7 DOF control of the FTS arms.

Part Two

The following script provides a representiative timeline for the end-to-end changeout of one IEA ORU. The previously identified assembly complete configuration was assumed and the script details the associated truss bay locations with respect to specific activities. The steps were developed collectively by the robotics task team that included the robotic developers who provided information concerning specific activities and associated times (for example the power up of the equipment). The translational rates of the mobile transporter were taken from data provided by McDonnell Douglas. When data were not available, the best estimate was assigned to that particular subtask.

End-To-End Changeout of Orbital Replacement Unit (ORU) on the Integrated Equipment Assembly (IEA) using the Flight Telerobotic Servicer (FTS)

Assumptions:

1. ASPS was not used.
2. FTS uses MST (2).
3. Visual targets on end effector interface.
4. ORU stabilization and end effector interface are the same position.
5. Loading of MSTs on FTS's arms is an automated sequence.

<u>Script</u>	<u>TIME</u> (MINUTES)
<u>A. MSC power up (from cold start).</u>	
1. MT software and electrical.	60:00
MT hardware.	60:00
SSRMS software and electrical.	30:00
SSRMS mechanical.	60:00
Total	3.5 hours

B.	FTS power up.	15:00
C.	MSC traverse/load FTS	
1.	MSC translates from SB7-FF to SB2-FF (utility port) 5 bays	
	Meets micro-g requirements.	16:00 [1]
	Violates micro-g requirements.	8:00
2.	SSRMS unstow.	5:00
3.	SSRMS extends to grapple FTS.	3:00
4.	SSRMS aligns to grapple FTS.	2:00
5.	SSRMS grapple FTS.	0:30
6.	SSRMS positions FTS to stowage position on MSC base.	3:00
7.	SSRMS stows FTS.	12:00
8.	Stow SSRMS.	2:00
Total		.73 hours
D.	FTS loads MST on both arms.	2:00
E.	MSC Traverse to Unpressurized Logistics Carrier (ULC).	
1.	MSC translates from SB2-FF to PB2-FF 3 bays	
	Meets micro-g requirements.	9:00
	Violates micro-g requirements.	5:00
F.	FTS loads ORU from ULC.	
1.	Unstow SSRMS.	2:00
2.	SSRMS extends to grapple FTS.	2:00
3.	SSRMS aligns to grapple FTS.	1:00
4.	SSRMS grapples FTS.	0:30
5.	SSRMS positions FTS at ORU on ULC.	3:00
6.	Extend right end effector to right stabilization interface point.	0:30
7.	Align right end effector for insertion into right stabilization interface.	4:00
8.	Insert end effector into right stabilization interface.	1:00
9.	Extend left end effector to new ORU end effector interface.	0:30
10.	Align left end effector for insertion into left end effector interface	4:00
11.	Insert left end effector into left interface	1:00
12.	Left MST unscrews bolt.	3:00

[1] J. Renshall/Astro, "Motion Anlysis for Battery/Umbilical Trade Study", AST-MDSSC 137, 2/20/89.

13.	Left end effector withdraws from interface.	0:30
14.	Extend left end effector to left stabilization interface.	0:30
15.	Align left end effector for insertion into left stabilization interface.	3:00
16.	Insert left end effector into left stabilization interface.	1:00
17.	Withdraw right arm from right stabilization point.	0:30
18.	Extend right end effector to right end effector interface.	0:30
19.	Align right end effector for insertion into right end effector interface.	3:00
20.	Insert right end effector into right end effector interface.	1:00
21.	Right MST unscrews bolt.	3:00
22.	Withdraw right end effector (with new ORU) clear of adjacent ORUs.	1:00
23.	Left end effector withdraws from left stabilization interface to home position.	0:30
24.	SSRMS positions FTS (with new ORU) to ORU stowage position on MSC.	3:00
25.	Left arm unstows.	0:30
26.	Left arm extends to stabilization interface.	0:30
27.	Left end effector aligns for insertion into left stabilization interface	4:00
28.	Left end effector inserts into left stabilization interface.	1:00
29.	Right arm extends end effector (with new ORU) for MSC stowage.	0:30
30.	Right end effector aligns new ORU for stowage.	5:00
31.	Right end effector inserts new ORU to storage location.	7:00
32.	Right MST screws down bolt.	3:00
33.	Right end effector withdraws from right end effector interface.	0:30
34.	Extend right end effector to stabilization interface.	0:30
35.	Align right end effector for insertion into right stabilization point.	3:00
36.	Insert right end effector into right stabilization point.	1:00
37.	Left end effector withdraws from left stabilization interface.	0:30
38.	Left end effector extends to left end effector interface on new ORU.	0:30
39.	Left end effector aligns for insertion into left end effector interface.	3:00
40.	Left end effector inserts into left end effector interface.	1:00
41.	Left MST screws down left bolt.	3:00
42.	Left arm withdraws from left interface and stows.	0:30
43.	SSRMS stows FTS on MSC.	12:00
44.	Stow SSRMS.	2:00
Total		1.48 hours

G. <u>MSC traverse bays.</u>

1.	MSC translates from PB2-FF to SA4-FF 14 bays	
	Meets micro g.	43:00
	Violates micro g.	23:00
2.	MSC rotates 90 deg, plane changes to SA4-UF	
	Meets micro g.	8:00
	Violates micro g.	6:00
3.	MSC plane changes to SA4-AF, rotates 90 deg	
	Meets micro g.	8:00
	Violates micro g.	6:00
4.	MSC translates from SA4-AF to SA3-AF (utility port)	
	Meets micro g.	3:00
	Violates micro g.	2:00
5.	SSRMS unstows.	2:00
6.	SSRMS positions to grapple FTS.	2:00
7.	SSRMS aligns to grapple FTS.	1:00
8.	SSRMS grapple FTS.	0:30
9.	SSRMS positions FTS above truss bay surrounding IEA.	3:00
Total		1.18 hours

H. <u>FTS removes/installs ORU.</u>

1.	FTS unstows arms to home position.	1:00
2.	SSRMS positions FTS to worksite.	12:00
3.	Extend right end effector to right stabilization interface point.	0:30
4.	Align right end effector for insertion into right stabilization interface.	4:00
5.	Insert end effector into right interface point.	1:00
6.	Extend left end effector to old ORU end effector interface	0:30
7.	Align left end effector for insertion into left end effector interface	4:00
8.	Insert left end effector into left interface	1:00
9.	Left MST unscrews bolt.	3:00
10.	Left end effector withdraws from interface.	0:30
11.	Extend left end effector to left stabilization point.	0:30
12.	Align left end effector for insertion into left stabilization point.	3:00
13.	Insert left end effector into left stabilization point.	1:00
14.	Withdraw right arm from right stabilization point.	0:30
15.	Extend right end effector to right old ORU end effector interface.	0:30

16.	Align right end effector for insertion into right end effector interface.	3:00
17.	Insert right end effector into right end effector interface.	1:00
18.	Right MST unscrews bolt.	3:00
19.	Withdraw right end effector (with old ORU) clear of adjacent ORUs.	1:00
20.	Left end effector withdraws from left stabilization interface to home position.	0:30
21.	SSRMS withdraws FTS from worksite position.	12:00
22.	SSRMS positions FTS (with old ORU) to MSC storage location.	3:00
23.	Left arm unstows.	0:30
24.	Left arm extends to stabilization interface.	0:30
25.	Left end effector aligns for insertion into left stabilization interface.	4:00
26.	Left end effector inserts into left stabilization interface.	1:00
27.	Right arm extends end effector (with old ORU) to stowage location.	0:30
28.	Right end effector orients old ORU above storage location.	5:00
29.	Right end effector inserts old ORU into storage location.	3:00
30.	Right MST screws down bolt.	3:00
31.	Right end effector withdraws from Right end effector interface.	0:30
32.	Extend right end effector stabilization interface.	0:30
33.	Align right end effector fo insertion into right stabilization point.	3:00
34.	Insert right end effector into right stabilization point.	1:00
35.	Left end effector withdraws from left stabilization interface.	0:30
36.	Left end effector extends to left end effector interface on old ORU.	0:30
37.	Left end effector aligns for insertion into left end effector interface.	3:00
38.	Left end effector inserts into left end effector interface.	1:00
39.	Left MST screws down left bolt.	3:00
40.	Left arm withdraws from left interface.	0:30
41.	SSRMS positions FTS to new ORU.	2:00
42.	Extend right end effector to right stabilization interface point.	0:30
43.	Align right end effector for insertion into right stabilization interface.	4:00
44.	Insert end effector into right interface point.	1:00
45.	Extend left end effector to new ORU end effector interface.	0:30
46.	Align left end effector for insertion into left end effector interface.	4:00
47.	Insert left end effector into left interface.	1:00
48.	Left MST unscrews bolt.	3:00
49.	Left end effector withdraws from interface.	0:30
50.	Extend left end effector to left stabilization point.	0:30

51.	Align left end effector for insertion into left stabilization point.	3:00
52.	Insert left end effector into left stabilization point.	1:00
53.	Withdraw right arm from right stabilization point.	0:30
54.	Extend right end effector to right new ORU end effector interface.	0:30
55.	Align right end effector for insertion into right end effector interface.	3:00
56.	Insert right end effector into right interface.	1:00
57.	Right MST unscrews bolt.	3:00
58.	Right end effector withdraws (with new ORU) to home position.	0:30
59.	SSRMS positions FTS (with new ORU) to above truss bay at worksite.	3:00
60.	SSRMS positions FTS to worksite.	12:00
61.	Left arm unstows.	0:30
62.	Left arm extends to stabilization interface.	0:30
63.	Left end effector aligns for insertion into left stabilization interface.	4:00
64.	Left end effector inserts into left stabilization interface.	1:00
65.	Right arm extends end effector (with new ORU) to empty ORU slot.	0:30
66.	Right end effector orients new ORU above empty ORU slot.	5:00
67.	Right end effector inserts old ORU into storage location.	3:00
68.	Right MST screws down bolt.	3:00
69.	Right end effector withdraws from Right end effector interface.	0:30
70.	Extend right end effector to stabilization interface.	0:30
71.	Align right end effector for insertion into right stabilization point.	3:00
72.	Insert right end effector into right stabilization point.	1:00
73.	Left end effector withdraws from left stabilization interface.	0:30
74.	Left end effector extends to left end effector interface on new ORU.	0:30
75.	Left end effector aligns for insertion into left end effector interface.	3:00
76.	Left end effector inserts into left end effector interface.	1:00
77.	Left MST screws down left bolt.	3:00
78.	Left arm withdraws from left interface.	0:30
79.	Right arm withdraws from stabilization point.	0:30
80.	Both arms stow.	1:00
81.	SSRMS withdraws FTS out of truss.	12:00
82.	SSRMS positions FTS to MSC stowage position.	3:00
83.	SSRMS stow FTS.	12:00
84.	SSRMS stows.	2:00
	Total	3.23 hours

I. <u>System checkout - worksite cleanup.</u> 10:00

J. <u>MSC traverse to ORU dump.</u>

1. Repeat G. in reverse. 70:00

K. <u>ORU offload.</u>

1. Repeat F in reverse. 89:00

L. <u>MSC traverse from ULC to SB2-FF.</u>

1. Repeat E in reverse. 9:00

M. <u>FTS unloads tools.</u>

1. Repeat D in reverse. 2:00

N. <u>MSC unloads FTS/traverses to MSC stowage bay.</u>

1. Repeat C in reverse. 52:00

O. <u>FTS powerdown.</u> 10:00

P. <u>MSC powerdown.</u> 30:00

Total 897:00 min

Part Three

ORDER OF SCRIPTS

ORDER OF SCRIPTS		PAGE
1) Luminare/Camera Changeout - FTS	semi-automatically	37
2) Luminare/Camera Changeout - SPDM	semi-automatically	41
3) Startracker Changeout - FTS	semi-automatically	43
4) Startracker Changeout - SPDM	semi-automatically	46
5) IEA / ORU Changeout - FTS	semi-automatically	49
6) IEA / ORU Changeout - SPDM	semi-automatically	55
7) Debris Shield / TCS Manifold - SPDM	semi-automatically	60
8) SPDM ORU Changeout - FTS	teleoperated	67
9) Beta Gimbal Changeout - FTS	teleoperated	70
10) Beta Gimbal Changeout - SPDM	teleoperated	74
11) MT Battery Changeout - FTS	teleoperated	77
12) MT Battery Changeout - SPDM	teleoperated	80
13) IEA / ORU Changeout -	teleoperated	83

Figure H4-9 depicts the SSF model that was used for this analysis. The numbered locations indicate where the task was performed on the Space Station and correspond to the previous listing of tasks.

Script for Changeout of Truss Mounted Camera/Luminare Orbital Replacement Unit (ORU) using Flight Telerobotic Servicer (FTS)

Synopis:

The SSRMS unstows and grapples the FTS on the MSC. The SSRMS transports the FTS to the worksite where the FTS stabilizes with the ASPS. The FTS removes the expended ORU with one arm and replaces it with the replenishment ORU on the other arm. The FTS then releases the ASPS and is transported back to the MSC by the SSRMS. The SSRMS then stows itself.

Assumptions:

1. The Camera/Luminare was designed to be robotically serviced.
2. The FTS performs the ORU exchange while attached to SSRMS.
3. Auto-sequence/trajectories will be utilized where sufficiently accurate positional information exists.
4. All auto-sequences will be joint angle trajectories not POR trajectories.
5. Camera/Luminare is attached to truss node ball via H-type connector that is FTS driveable with a gripper/nut-runner tool.
6. FTS is stowed on MSC FTS interface WAF/PDGF Location #7

Required Tools: Node Attachment Tool (NAT)

Script

H1. FTS removes/installs ORU	TIME
1. Adjust SSRMS elbow cameras for operation viewing.	0:35
2. SSRMS executes auto-sequence to position and align for grapple of FTS.	1:30
3. SSRMS manually grapples FTS.	1:00
4. FTS/ASPS releases WAF/PDGF location #5.	0:30
5. FTS executes ASPS stow auto-sequence.	1:45
6. SSRMS executes auto-sequence maneuver to position FTS at worksite.	1:40
7. Position SSRMS elbow camera for operation viewing.	0:35
8. Acquire NAT.	3:00
9. Execute ASPS stabilization auto-sequence:	0:40
a. Extend ASPS/NAT to stabilization interface point.	
b. Align ASPS/NAT arm for capture of stabilization interface point.	
c. Capture stabilization point.	

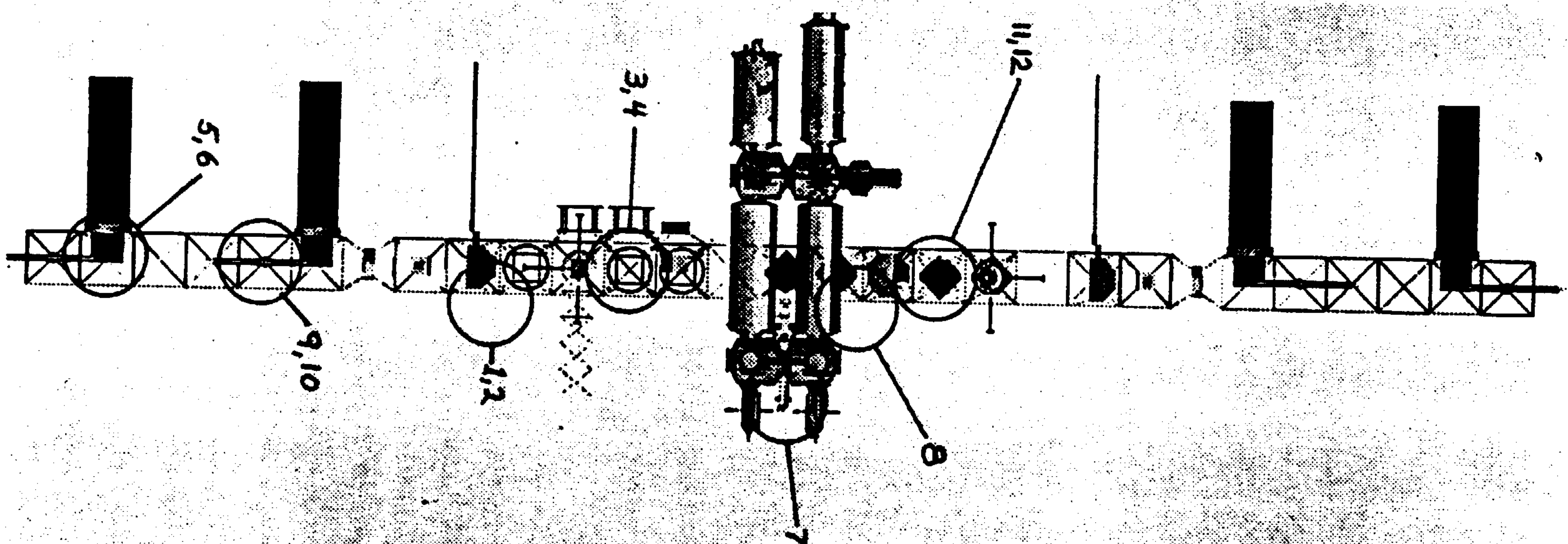


Figure H4-9. Task Worksite Areas, Top View

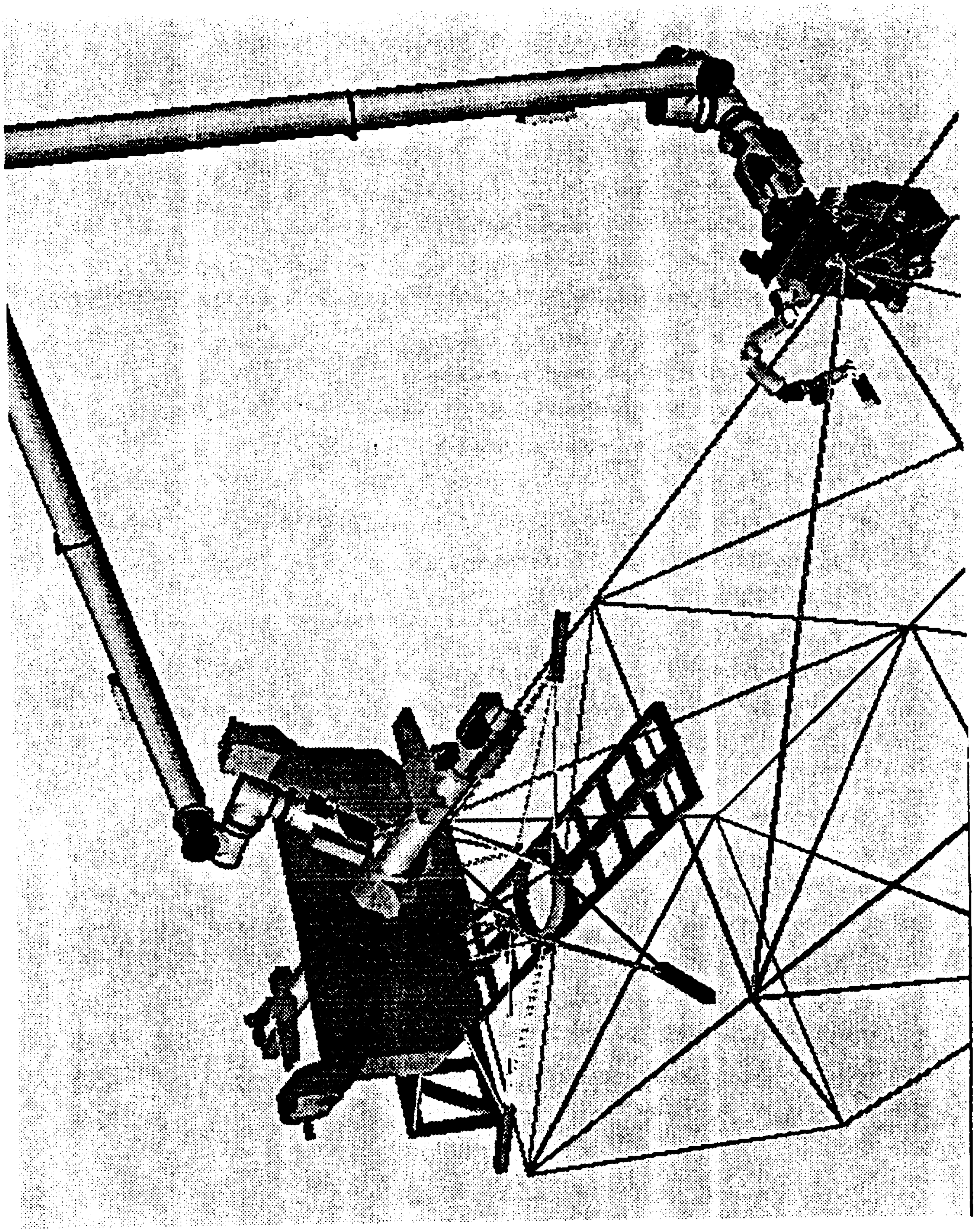


Figure H4-10. Luminare/Camera Changeout - FTS

	a. Extend ASPS/NAT to stabilization interface point.	
	b. Align ASPS/NAT arm for capture of stabilization interface point.	
	c. Capture stabilization point.	
10.	Execute left arm auto-sequence:	2:50
	a. Extend reference arm to Camera/Luminare location.	
	b. Align task arm for insertion of tool into H-type connector.	
11.	Manual insertion into H-type connector.	0:20
12.	Accurately log ORU position, store local reference frame & adjust subsequent auto-sequences as required.	1:00
13.	Drive H-type fastener to released position.	0:30
14.	Execute left arm release/retract auto-sequence:	2:50
	a. Withdraw task arm from stabilization interface.	
	b. Retract right arm from ORU maintenance worksite.	
	c. Stow left arm.	
15.	Execute right arm positioning & installation auto-sequence:	3:40
	a. Extend task arm to ORU installation worksite.	
	b. Align ORU for installation.	
	c. Install ORU.	
16.	Execute right arm release/retract auto-sequence:	3:10
	a. Withdraw task arm from stabilization interface.	
	b. Retract right arm from ORU maintenance worksite.	
	c. Stow left arm.	
17.	Standby for ORU checkout.	
18.	Retract ASPS/NAT from stabilization interface point.	0:40
19.	Stow NAT.	3:00
20.	Execute SSRMS auto-sequence to position FTS for stow on MSC WAF/PDGF location #5.	1:40
21.	FTS ASPS capture of MSC WAF/PDGF location #5.	1:00
22.	SSRMS releases FTS.	0:30
23.	SSRMS executes stow auto-sequence .	1:30
	Total	33:55

Script for Changeout of Truss Mounted Camera/Luminare Orbital Replacement Unit (ORU) using Special Purpose Dexterous Manipulator (SPDM)

Synopis:

The SPDM is located on the MSC and unfolds its body to position its head near the worksite. SPDM then reachs out and stabilizes with one arm and grasps the expended ORU with the other arm. SPDM stows the expended ORU on its ORU storage pad and grasps the replenishment ORU. It then installs the ORU, stows both arms, and stows its body.

Assumptions:

1. The Camera/Luminare was designed to be robotically serviced.
2. The SPDM performs the ORU exchange while attached to MSC PDGF Location #6.
3. Auto-sequence/trajectories will be utilized where sufficiently accurate positional information exists.
4. All auto-sequences will be joint angle trajectories not POR trajectories.
5. Camera/Luminare is attached to truss node ball via H-type connector that is SPDM driveable with Type L compound TCM.

Script	Time
H2. SPDM removes/installs ORU	
1. Position SSRMS cameras for operation viewing	1:30
2. Execute SPDM body auto-sequence to position body near worksite	1:32
3. Adjust SPDM head cameras	1:15
4. Execute stabilization auto-sequence:	1:30
a. Extend reference arm to stabilization interface point (node pin)	
b. Align reference arm for capture of stabilization interface point (node pin)	
5. Manual capture of stabilization point/node pin.	0:40
6. Execute task arm auto-sequence:	1:37
a. Extend reference arm to expended ORU location.	
b. Align task arm for capture of expended ORU.	
7. Manual capture of expended ORU.	0:45
8. Accurately log ORU position & adjust subsequent auto-sequences as required.	1:00
9. Execute task arm ORU stow auto-sequence:	2:20
a. Withdraw expended ORU.	
b. Align expended ORU for stow on SPDM body.	
c. Insert expended ORU into stow location.	
d. Release ORU.	

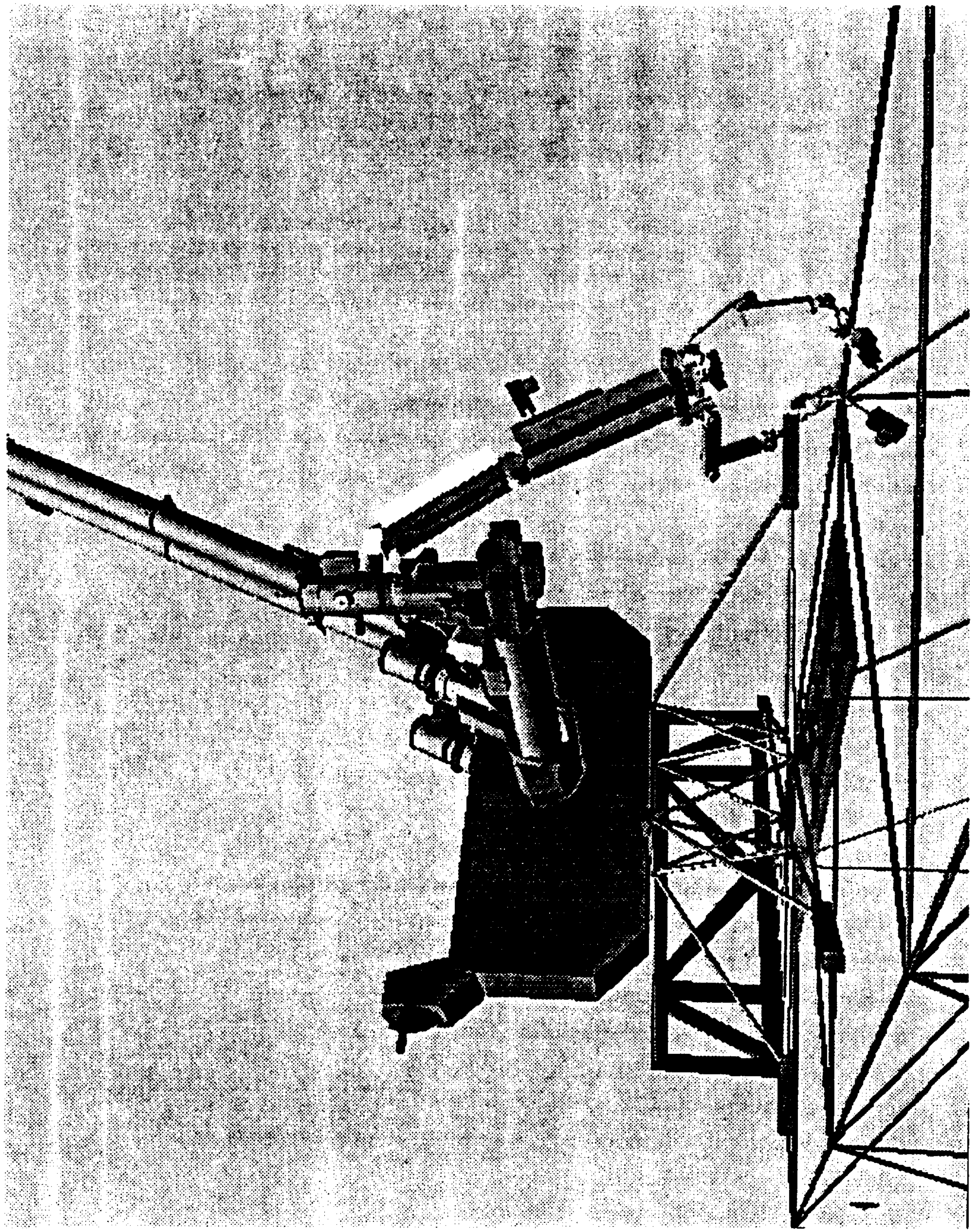


Figure H4-11. Luminare/Camera Changeout - SPDM

10.	Execute task arm grapple auto-sequence to acquire replenishment ORU:	2:00
	a. Withdraw task arm.	
	b. Align task arm to grapple replenishment ORU.	
	c. Grapple replenishment ORU.	
11.	Execute task arm positioning auto-sequence:	1:47
	a. Withdraw ORU from stowed location.	
	b. Extend task arm to ORU installation worksite.	
	c. Align ORU for installation.	
12.	Install and release replenishment ORU.	0:45
13.	Standby for ORU checkout.	
14.	Execute task arm stow auto-sequence.	1:10
15.	Execute reference arm stow auto-sequence.	1:30
16.	Execute body stow auto-sequence.	1:30
	Total	20:51min

Script for Changeout of Startracker Orbital Replacement Unit (ORU) using Flight Telerobotic Servicer (FTS)

Synopsis:

The SSRMS unstows and grapples the FTS located on the MSC. The SSRMS transports the FTS to the worksite where it connects to the GN&C pallet via a WAF. The FTS grasps the expended startracker with one arm and replaces it with the one on the other arm. The FTS releases from the GN&C pallet and is transported back to the MSC by the SSRMS. The SSRMS then stows itself.

Assumptions:

1. The startracker was designed to be robotically serviced.
2. The FTS performs the ORU exchange while attached to SSRMS.
3. Auto-sequence/trajectories will be utilized where sufficiently accurate positional information exists.
4. All auto-sequences will be joint angle trajectories not POR trajectories.
5. Startracker is attached to truss node ball via H-type connector that is FTS driveable with gripper/nut-runner tool.
6. FTS is stowed on MSC FTS interface WAF/PDGF Location #6.

Script

H1. FTS removes/installs ORU	Time
1. Position SSRMS cameras for operation viewing.	0:45

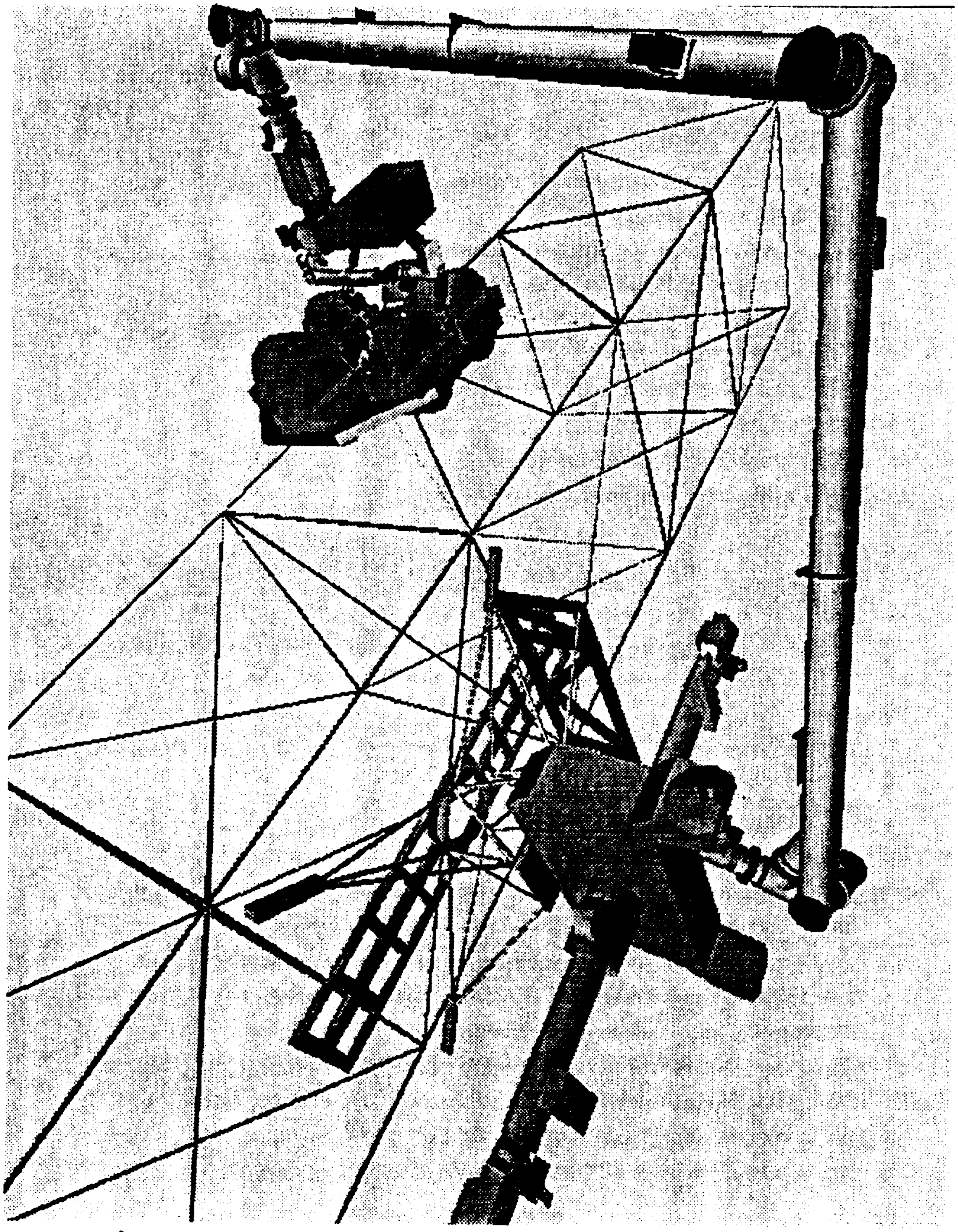


Figure H4-12. Startracker Changeout -FTS

2. SSRMS executes unstow auto-sequence.	1:10
3. SSRMS aligns for grapple of FTS.	0:15
4. SSRMS manually grapples FTS.	1:00
5. FTS releases WAF/PDGF location #6.	0:30
6. FTS executes ASPS retract auto-sequence.	2:20
7. SSRMS executes auto-sequence maneuver to position FTS at worksite.	0:55
8. Position SSRMS elbow camera for operation viewing.	0:45
9. FTS extends ASPS to WAF.	2:20
10. ASPS attaches to WAF.	1:00
11. Execute right arm auto-sequence:	1:10
a. Extend reference arm to startracker location.	
b. Align task arm for insertion of tool into H-type connector.	
12. Manual insertion into H-type connector.	0:20
13. Accurately log ORU position, store local reference frame & adjust subsequent auto-sequences as required.	1:00
14. Drive H-type fastener to released position.	0:30
15. Execute right arm release/retract auto-sequence:	1:15
a. Withdraw right arm from stabilization interface.	
b. Retract right arm from ORU maintenance worksite.	
c. Return right arm to home position.	
16. Execute replenishment ORU installation auto-sequence:	2:15
a. Position left arm.	
b. Align left arm for installation of replenishment ORU.	
c. Install replenishment ORU.	
17. Release replenishment ORU.	0:30
18. Return left arm to home position.	1:20
19. ASPS release WAF.	0:30
20. ASPS retract.	2:20
21. SSRMS positions FTS on MSC.	0:55
22. FTS extends ASPS.	2:20
23. SSRMS releases FTS.	0:30
24. SSRMS stows.	1:10
Total	27:05

Script for Changeout of Startracker Orbital Replacement Unit (ORU) using Special Purpose Dexterous Manipulator (SPDM)

Synopsis:

The SSRMS unstows and grapples the SPDM located on the MSC. The SSRMS transports the SPDM to the worksite where it grasps a stabilization interface point with one arm. It uses its free arm to grasp the expended startracker and places it onto its ORU storage pad. It grasps the replenishment ORU from the pad and installs it. The SPDM then releases the stabilization interface and is placed back on the MSC. The SSRMS then stows itself.

Assumptions:

1. The startracker was designed to be robotically serviced.
2. The SPDM performs the ORU exchange while attached to SSRMS.
3. Auto-sequence/trajectories will be utilized where sufficiently accurate positional information exists.
4. All auto-sequences will be joint angle trajectories not POR trajectories.
5. Startracker is attached to CMG pallet via H-type connector that is SPDM driveable with Type L compound TCM.
6. SPDM is stowed on MSC PDGF Location #6.
7. SPDM has replenishment ORU stowed on body.

Script	Time
H2. SPDM removes/installs ORU	
1. Position SSRMS cameras for operation viewing.	0:45
2. SSRMS executes unstow auto-sequence.	1:20
3. SSRMS executes auto-sequence to position and align for grapple of SPDM.	0:20
4. SSRMS manually grapples SPDM.	1:00
5. SPDM releases PDGF location #6.	0:30
6. SSRMS executes auto-sequence maneuver to position SPDM at worksite.	0:55
7. Position SSRMS elbow camera for operation viewing.	0:45
8. Execute SPDM body auto-sequence to position body near worksite (CMG Pallet).	1:20
9. Position SPDM head cameras.	0:30
10. Execute stabilization auto-sequence:	1:00
a. Extend reference arm to stabilization interface point.	
b. Align reference arm for capture of stabilization interface point.	
11. Manual capture of stabilization point.	0:20

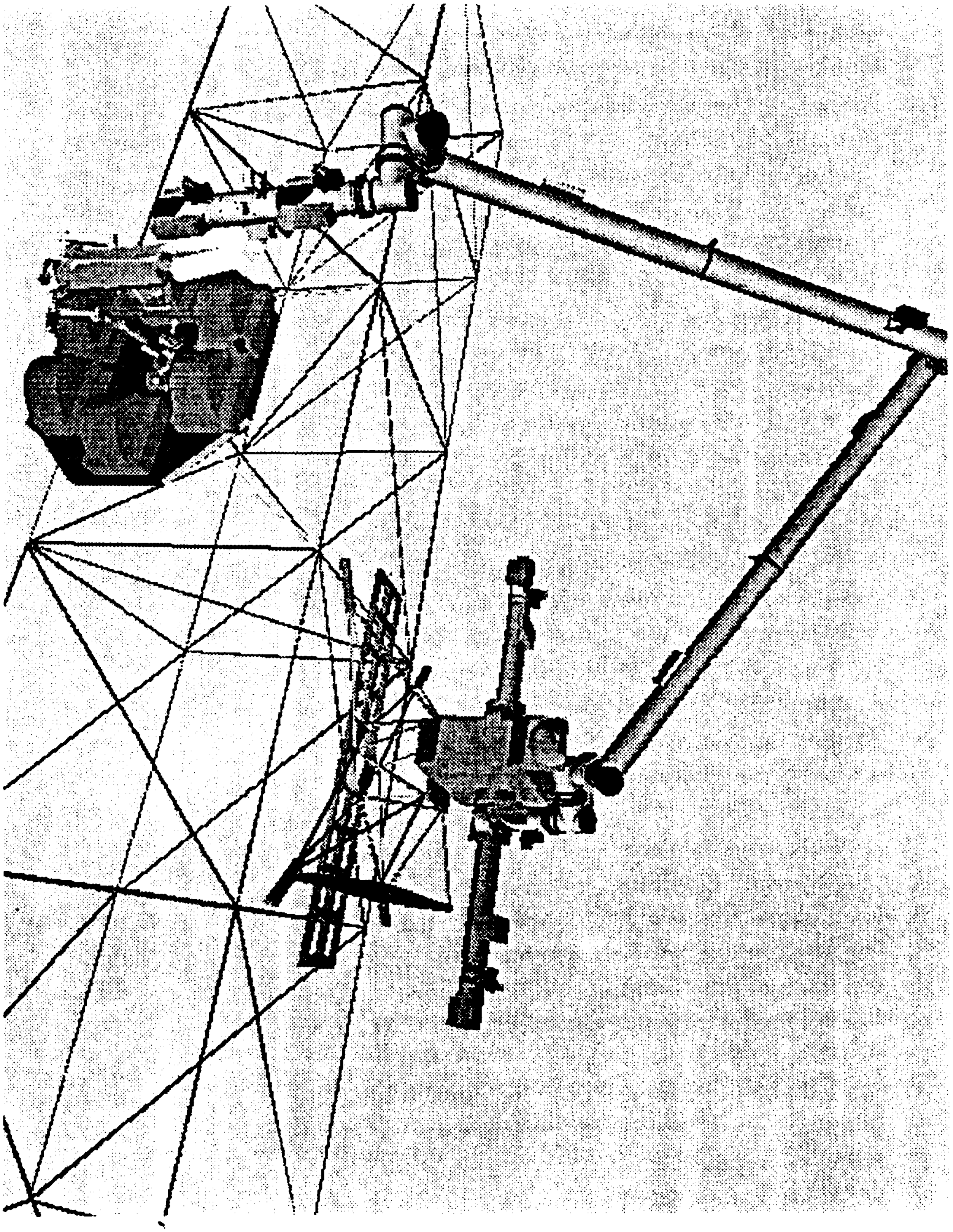


Figure H4-13. Startracker Changeout - SPDM

12.	Execute task arm auto sequence:	1:55
	a. Extend reference arm to startracker location.	
	b. Align task arm for insertion of tool into H-type connector.	
13.	Manual insertion into H-type connector.	0:20
14.	Accurately log ORU position, store local reference frame & adjust subsequent auto-sequences required.	1:00
15.	Drive H-type fastener to released position.	0:45
16.	Execute task arm ORU stow auto-sequence:	2:20
	a. Withdraw expended ORU .	
	b. Align expended ORU for stow on SPDM body.	
	c. Insert expended ORU into stow location.	
	d. Release ORU.	
17.	Execute task arm grapple auto-sequence to acquire replenishment ORU	0:30
	a. Withdraw task arm.	
	b. Align task arm to grapple replenishment ORU.	
	c. Grapple replenishment ORU.	
18.	Execute task positioning auto-sequence:	0;45
	a. Withdraw ORU from stowed location.	
	b. Extend task arm to ORU installation worksite.	
	c. Align ORU for installation.	
19.	Execute replenishment ORU installation auto-sequence:	0:20
	a. Insert ORU into interface.	
	b. Release ORU.	
	c. Withdraw task arm.	
20.	Standby for ORU checkout.	
21.	Execute task arm stow auto-sequence.	2:25
22.	Execute reference arm stow auto-sequence.	0:55
23.	Execute body stow auto-sequence.	2:55
24.	Execute SSRMS auto-sequence to position SPDM for stow on MSC PDGF location #6.	0:55
25.	Manual stow of SPDM on MSC PDGF location #6.	0:30
26.	SPDM capture of MSC PDGF location #6.	1:00
27.	SSRMS releases SPDM.	0:30
28.	SSRMS executes stow auto-sequence.	1:10
	Total	27:00 min

Changeout of the Orbital Replacement Unit (ORU) on the Integrated Equipment Assembly (IEA) using the Flight Telerobotic Servicer (FTS)

(Semi-automatically)

Synposis:

In this task the FTS will first be captured by the Space Station Remote Manipulator (SSRMS), which is mounted on the Mobile Servicing Center (MSC), and moved inside the truss over the ORU needing to be replaced on the IEA. The FTS will then stabilize and disconnect the expended ORU. The FTS then releases the IEA worksite and is moved by the SSRMS to the dry cargo sub-carrier on the MSC carrying the expended ORU. The FTS stows the expended ORU and retrieves a replacement from the dry cargo sub carrier. The SSRMS again moves the FTS to The IEA worksite. The replacement ORU is connected, and the FTS stows itself, is withdrawn from the truss, and transported back to the MSC by the SSRMS.

Assumptions:

1. The FTS performs the ORU exchange while attached to the SSRMS end effector.
2. FTS uses two (2) User-Provided Tools (UPT).
3. Auto-sequence/trajectories will be utilized where sufficiently accurate positional information exists.
4. Visual targets exist on the UPT interfaces.
5. ORU structural interface and the UPT stabilization are the same.
6. Replenishment and expended ORUs are sufficiently attached to the ORU location on the MSC by a single structural interface bolt.
7. All auto-sequences will be joint angle trajectories not POR trajectories.
8. FTS Attachment, Stabilization and Positioning Subsystem (ASPS) is not used for the ORU exchange.

Script	Time
H1. FTS removes/installs IEA ORU TIME	
1. SSRMS executes unstow auto-sequence.	0:45
2. SSRMS executes auto-sequence to position and align for grapple of FTS.	0:15
3. SSRMS manually grapples FTS.	1:00
4. FTS ASPS releases Worksite Attach Fixture (WAF)/PDGF location #8.	1:25
5. SSRMS executes auto-sequence maneuver to position FTS at worksite.	1:40
6. Position SSRMS elbow camera for operation viewing.	0:35
7. Position FTS head cameras for operational viewing.	0:35

8. Unstow left arm with UPT attached and move to entry sphere of first stabilization auto-sequence.
9. Execute left UPT stabilization auto-sequence:
   a. Extend left UPT to first UPT stabilization interface point.

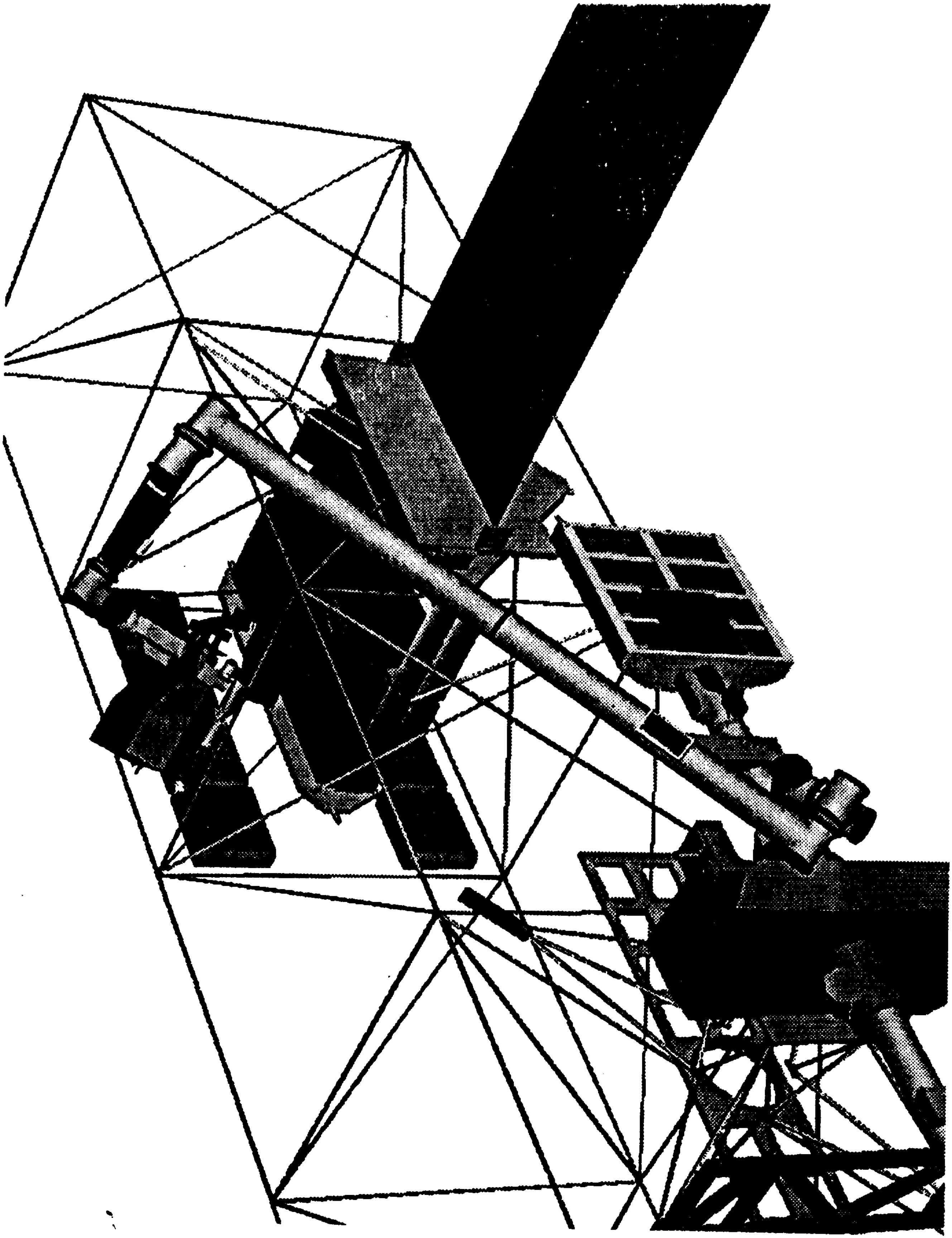


Figure H4-14. IEA /ORU Changeout FTS

b. Align left UPT for insertion into first UPT stabilization interface point. 4:00

10. Manually insert left UPT into first UPT stabilization interface. 0:50
11. Unstow right arm and position its UPT within entry sphere of positioning auto-sequence.
12. Execute right UPT positioning auto-sequence:
    a. Extend right UPT to location of expended ORU's first structural interface point.
    b. Align right UPT for insertion into expended ORU's first structural interface point. 2:10
13. Manually insert right UPT into first structural interface of expended ORU. 1:00
14. Accurately log first UPT stabilization interface point position and ORU position. Use this data to adjust subsequent auto-sequences as required. 1:00
15. Execute expended ORU detach auto-sequence:
    a. Unbolt expended ORU's first structural interface with right UPT. 1:00
    b. Release ORU.
    c. Withdraw right UPT from ORU's first structural interface.
    d. Extend right UPT to second UPT stabilization interface point.
    e. Align right UPT to second UPT stabilization interface point. 1:10
16. Manually insert right UPT into second UPT stabilization interface point. 1:00
17. Accurately log second UPT stabilization interface point and adjust subsequent right arm auto-sequences as required. 1:00
18. Execute left UPT positioning auto-sequence:
    a. Detach left UPT from first UPT stabilization interface point.
    b. Withdraw left UPT from first UPT stabilization interface.
    c. Extend left UPT to location of expended ORU's second structural interface point.
    d. Align left UPT for insertion into expended ORU's second structural interface point. 1:20
19. Manually insert left UPT into second structural interface of expended ORU. 1:00
20. Accurately log ORU position. Use this data to adjust subsequent left arm auto-sequences as required. 1:00

21.	Execute ORU detach auto-sequence:	
	a. Unbolt expended ORU's first structural interface with left UPT.	
	b. Withdraw left UPT with expended ORU attached.	1:00
22.	Execute right UPT release/retract auto-sequence.	
	a. Detach right UPT from second UPT stabilization interface point.	
	b. Withdraw right UPT from second UPT stabilization interface.	
	c. Retract right arm from ORU maintenance worksite.	
23.	Execute right arm stow auto-sequence.	2:30
24.	SSRMS withdraws FTS from worksite position.	
25.	SSRMS positions FTS with expended ORU to MSC ORU storage location.	4:00
26.	Position SSRMS elbow camera for operation viewing.	0:35
27.	Position FTS head cameras for operational viewing.	0:35
28.	Unstow right arm and move to entry sphere of stabilization auto-sequence.	
29.	Execute right UPT stabilization auto-sequence:	
	a. Extend right UPT to MSC stabilization interface point.	
	b. Align right UPT for insertion into MSC stabilization interface point.	2:10
30.	Manually insert right UPT into MSC stabilization interface.	1:00
31.	Accurately log MSC position. Use this data to adjust subsequent auto-sequences as required.	1:00
32.	Execute left UPT positioning auto-sequence:	
	a. Extend expended ORU to MSC ORU storage location.	
	b. Align ORU for insertion into MSC ORU storage location.	1:10
33.	Manually insert expended ORU into MSC ORU storage location.	0:20
34.	Accurately log MSC ORU storage position. Use this data to adjust subsequent auto-sequences as required.	1:00
35.	Execute expended ORU stow auto-sequence:	
	a. Bolt expended ORU's first structural interface with left UPT.	1:00
	b. Release expended ORU.	
	c. Withdraw left UPT from ORU's second structural interface.	
36.	Execute replenishment ORU retrieval auto-sequence.	
	a. Extend left UPT to location of replenishment ORU's second structural interface point.	
	b. Align left UPT for insertion into replenishment ORU's second structural interface point.	

c. Insert left UPT into replenishment ORU's second structural interface point. 1:30

d. Unbolt replenishment ORU's second structural interface with left UPT. 1:00

e. Withdraw replenishment ORU from stowed location. 1:00

f. Withdraw left UPT with replenishment ORU attached. 1:30

37. Execute right UPT release/retract auto-sequence.

a. Detach right UPT from MSC stabilization interface point.

b. Withdraw right UPT from MSC stabilization interface.

c. Retract right arm from MSC ORU storage location.

38. Execute right arm stow auto-sequence. 2:30

39. SSRMS withdraws FTS from unpressurized logistics carrier.

40. SSRMS executes auto-sequence maneuver to position FTS at worksite position. 2:15

41. Position SSRMS elbow camera for operation viewing. 0:35

42. Position FTS head cameras for operational viewing. 0:35

43. Unstow right arm with UPT attached and move to entry sphere of second stabilization auto-sequence.

44. Execute right UPT stabilization auto-sequence:

a. Extend right UPT to second UPT stabilization interface point.

b. Align right UPT for insertion into second UPT stabilization interface point. 2:10

45. Manually insert right UPT into second UPT stabilization interface. 0:55

46. Execute replenishment ORU positioning auto-sequence:

a. Extend replenishment ORU to ORU maintenance worksite.

b. Align replenishment ORU for insertion into ORU maintenance worksite. 0:53

47. Manually insert replenishment ORU into ORU interface. 0:45

48. Accurately log ORU position. Use this data to adjust subsequent auto-sequences as required. 1:00

49. Execute replenishment ORU installation auto-sequence.

a. Bolt replenishment ORU into second structural interface with left UPT. 1:00

b. Release replenishment ORU.

c. Withdraw left UPT from replenishment ORU's second structural interface.

50. Execute left UPT stabilization auto-sequence:
    a. Extend left UPT to first UPT stabilization interface point.
    b. Align left UPT for insertion into first UPT stabilization interface point.
    c. Insert left UPT into first UPT stabilization interface point. 1:20
51. Execute right UPT positioning auto-sequence:
    a. Detach right UPT from second UPT stabilization interface point.
    b. Withdraw right UPT from second UPT stabilization interface.
    c. Extend right UPT to location of replenishment ORU's first structural interface point.
    d. Align right UPT for insertion into replenishment ORU's first structural interface point.
52. Execute replenishment ORU attach auto-sequence.
    a. Insert right UPT into replenishment ORU's first structural interface. 1:20
    b. Bolt replenishment ORU's into first structural interface with right UPT. 1:00
    c. Withdraw right UPT from ORU's first structural interface.
    d. Retract right arm from ORU maintenance worksite.
    e. Execute right arm stow auto-sequence. 2:30
53. Execute left UPT release/retract auto-sequence.
    a. Detach left UPT from first UPT stabilization interface point.
    b. Withdraw left UPT from first UPT stabilization interface.
    c. Retract left arm from ORU maintenance worksite.
    d. Execute left arm stow auto-sequence. 2:30
54. Standby for replenishment ORU checkout.
55. Execute SSRMS auto-sequence to position FTS for stow on MSC WAF/PDGF location #8. 1:40
56. Manual stow of FTS on MSC WAF/PDGF location #8. 0:15
57. FTS ASPS capture of MSC WAF/PDGF location #8. 0:40
58. SSRMS releases FTS. 0:30
59. Manual SSRMS back-off. 0:15
60. SSRMS moved to entry sphere of stow auto-sequence.
61. SSRMS executes stow auto-sequence. 0:45

    Total 70:54 min

Changeout of the Orbital Replacement Unit (ORU) on the Inegrated Equipment Assembly (IEA) using the Special Purpose Dexterous Manipulator (SPDM)

Synopsis:

In this task, the SPDM will first be captured by the Space Station Remote Manipulator (SSRMS), which is mounted on the Mobile Servicing Center (MSC), and transported to the worksite. Once at the worksite the SPDM will unstow and position itself inside the truss over the ORU needing to be replaced. The SPDM will then stabilize and disconnect the expended ORU. Once disconnected, the expended ORU is withdrawn from the worksite and stowed on the SPDM base. The SPDM then captures the replacement ORU, which is also on the SPDM base, and reconfigures his body and arms to reposition the replacement ORU into the worksite. The replacement ORU is connected, and the SPDM then withdraws from the truss, stows itself, and is transported back to the MSC by the SSRMS.

Assumptions:

1. The SPDM performs the ORU exchange while attached to the Space Station Remote Manipulator System (SSRMS) end effector.
2. SPDM uses two (2) User-Provided Tools (UPT).
3. Auto-sequence/trajectories will be utilized where sufficiently accurate positional information exists.
4. Visual targets exist on the UPT interfaces.
5. ORU structural interface and the UPT stabilization are the same.
6. Replenishment and expended ORUs are sufficiently attached to the ORU location on the SPDM body by a single structural interface bolt.
7. All auto-sequences will be joint angle trajectories not POR trajectories.
8. SPDM is stowed on MSC Power Data Grapple Fixture (PDGF) Location #6.

Script:

H2. SPDM removes/installs IEA ORU	Time
1. SSRMS executes unstow auto-sequence.	69 sec.
2. SSRMS executes auto-sequence to position and align for grapple of SPDM.	23 sec.
3. SSRMS manually grapples SPDM.	60 sec.
4. SPDM releases PDGF location #6.	30 sec.
5. SSRMS executes auto-sequence maneuver to position SPDM at worksite.	54 sec.
6. Position SSRMS elbow camera for operation viewing.	45 sec.
7. Execute SPDM body auto-sequence to position body near ORU maintenance worksite.	63 sec.
8. Position head cameras for operational viewing.	45 sec.

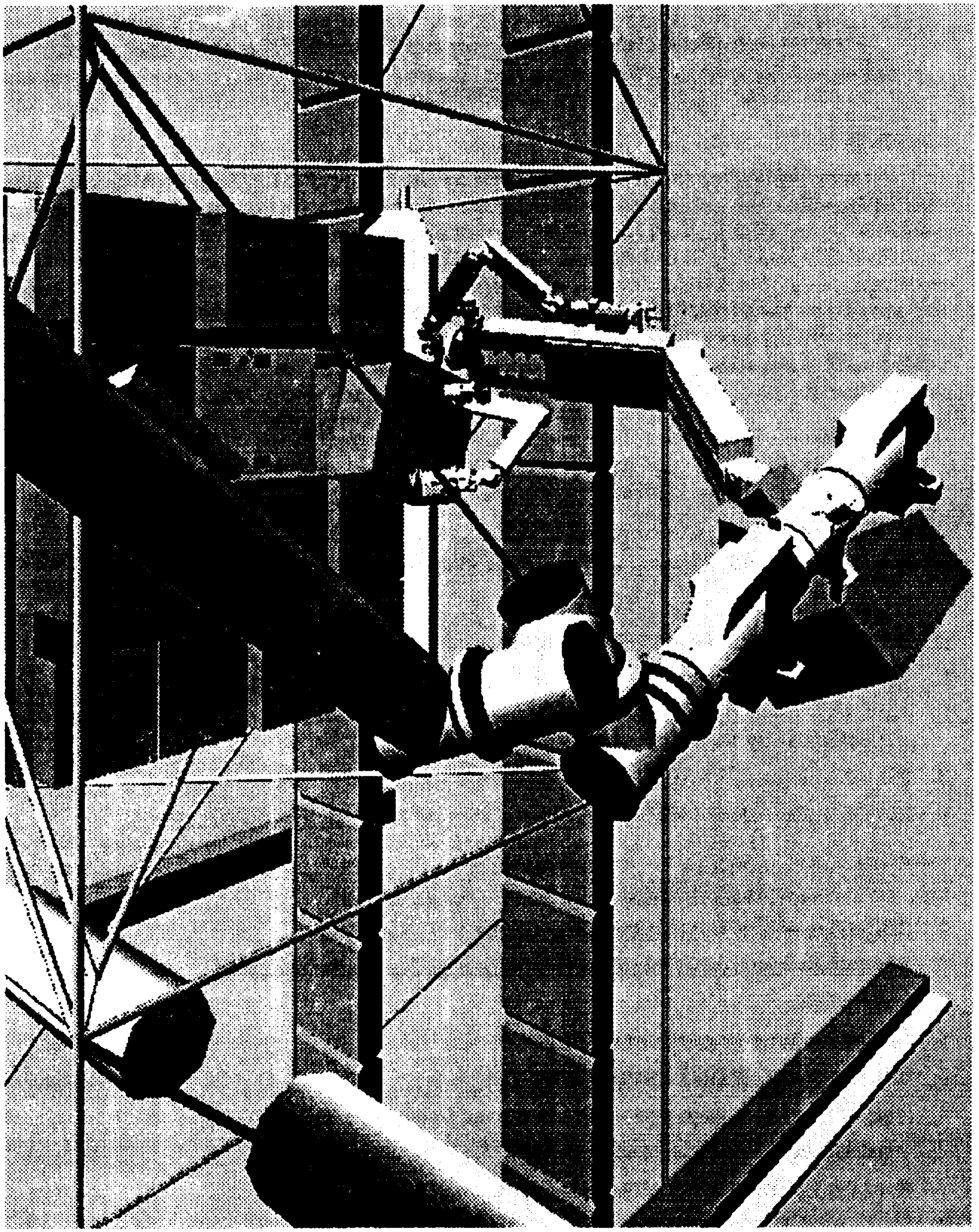


Figure H4-15. IEA/ORU Changeout - SPDM

9. Unstow right arm with UPT attached and move to entry sphere of first stabilization auto-sequence. 170 sec.
10. Execute right UPT positioning auto-sequence:
    a. Extend right UPT to location of expended ORU's first structural interface point.
    b. Align right UPT for insertion into expended ORU's first structural interface point.
11. Manually insert right UPT into first structural interface of expended ORU. 75 sec.
12. Accurately log first UPT structural interface point position and ORU position. Use this data to adjust subsequent auto-sequences as required. 60 sec.
13. Unstow left arm and position its UPT within entry sphere of positioning auto-sequence. 170 sec.
14. Execute left UPT positioning auto-sequence: ———
    a. Extend left UPT to location of expended ORU's second structural interface point.
    b. Align left UPT for insertion into expended ORU's second structural interface point.
15. Manually insert left UPT into second structural interface of expended ORU. 75 sec.
16. Accurately log second UPT structural interface point position and ORU position. Use this data to adjust subsequent auto-sequences as required 60 sec.
17. Execute expended ORU detach auto-sequence:
    a. Unbolt expended ORU's first structural interface with right UPT. 30 sec.
    b. Release ORU. 30 sec.
    c. Withdraw right UPT from ORU's first structural interface. ———
    d. Extend right UPT to first UPT stabilization interface point. ———
    e. Align right UPT to first UPT stabilization interface point. 25 sec.
18. Manually insert right UPT into first UPT stabilization interface point. 75 sec.
19. Accurately log first UPT stabilization interface point and adjust subsequent right arm auto-sequences as required. 60 sec.
20. Execute ORU detach/stow auto-sequence:
    a. Unbolt expended ORU's second structural interface with left UPT. 60 sec.
    b. Withdraw left UPT with expended ORU attached. 42 sec.

21. Execute right arm stow auto-sequence.	
a. Withdraw right arm from first stabilization point.	———
b. Stow right arm.	198 sec.
22. Execute body positioning auto-sequence in order to stow expended ORU.	158 sec.
23. Execute ORU detach/stow auto sequence.	
c. Align expended ORU for stow on SPDM base.	———
d. Insert expended ORU onto stow location on SPDM base.	96 sec.
e. Bolt expended ORU onto stow location with left UPT.	
f. Release expended ORU.	60 sec.
g. Withdraw left UPT from expended ORU	12 sec.
24. Execute body positioning auto-sequence in order to retrieve replenishment ORU.	104 sec.
25. Execute replenishment ORU retrieval auto-sequence.	
a. Extend left UPT to location of replenishment ORU's second structural interface point.	———
b. Align left UPT for insertion into replenishment ORU's second structural interface point.	47 sec.
c. Insert left UPT into replenishment ORU's second structural interface point.	10 sec.
d. Unbolt replenishment ORU's second structural interface with left UPT.	30 sec.
e. Withdraw left UPT with replenishment ORU attached.	84 sec.
26. Execute SPDM body auto-sequence to position body near ORU maintenance worksite.	192 sec.
27. Execute right UPT stabilization auto-sequence:	
a. Unstow right arm to first UPT stabilization interface point.	187 sec.
b. Align right UPT for insertion into first UPT stabilization interface point.	———
c. Insert right UPT into first UPT stabilization interface point.	11 sec.
28. Execute replenishment ORU installation auto-sequence.	
a. Extend left arm to ORU maintenance worksite.	37 sec.
b. Align ORU for installation.	———

c. Insert ORU into interface.	20 sec.
d. Bolt replenishment ORU into second structural interface with left UPT.	60 sec.
29. Execute right UPT positioning auto-sequence:	
a. Withdraw right UPT from first UPT stabilization interface point.	———
b. Align right UPT for insertion to ORU's first structural interface.	30 sec.
c. Insert right UPT into ORU's first structural interface.	15 sec.
30. Execute right UPT attach auto-sequence.	
a. Bolt replenishment ORU's into first structural interface with right UPT.	60 sec.
31. Standby for replenishment ORU checkout.	
32. Execute right arm stow auto-sequence:	
a. Release replenishment ORU.	30 sec.
b. Withdraw right UPT from replenishment ORU's first structural interface	180 sec.
c. Retract right arm from ORU maintenance worksite and stow.	———
33. Execute left arm stow auto-sequence:	
a. Release replenishment ORU.	30 sec.
b. Withdraw left UPT from replenishment ORU's second structural interface.	179 sec.
c. Retract left arm from ORU maintenance worksite and stow.	———
34. Execute body stow auto-sequence.	60 sec.
35. Execute SSRMS auto-sequence to position SPDM for stow on MSC PDGF location #6.	131 sec.
36. Manual stow of SPDM on MSC PDGF location #6	75 sec.
37. SPDM capture of MSC PDGF location #6	30 sec.
38. SSRMS releases SPDM	30 sec.
39. Manual SSRMS back-off	109 sec.
40. SSRMS positioned within entry sphere of stow auto-sequence	———
41. SSRMS executes stow auto-sequence	———
Total	59:77 min

Script for Changeout of the TCS Manifold Orbital Replacement Unit (ORU) using the Special Purpose Dexterous Manipulator (SPDM)

Synopsis:

The SSRMS unstows and grapples the SPDM located on the MSC (note: the new ORU is stored on the SPDM base attachment location). The SSRMS transports the SPDM to the node endcone worksite. To access the TCS manifold on the node endcone, the SPDM must unfasten and reposition two m/d shields covering the TCS manifold. Each shield has six fasteners the robot must turn a quarter turn with TBD tool #1 to unlatch; the SPDM uses its left arm to stabilize to various node handholds and uses its right arm to grasp TBD tool #1 and unscrew the fasteners. Once the shields are unfastened, the right arm stows the tool and the SSRMS repositions the SPDM to open the shields about their hinge point; the SPDM stabilizes to a handhold with the right arm and opens the left shield with the left arm, then reverses this procedure to open the right shield. After the m/d shields are opened, the SSRMS repositions the SPDM to access the TCS manifold attached to the node endcone. The SPDM stabilizes to a node handhold with its right arm, and with its left arm it unstows TBD tool #2; then the left arm unscrews two load-bearing connectors attaching the TCS manifold to the endcone. Upon unscrewing the second screw, the left arm stays attached to the connector and removes the ORU and stores it on a SPDM base attachment fixture. SPDM releases its right stabilization arm and retrieves the new ORU with this arm. The right arm hands off the new ORU to the left arm and restabilizes to the node handhold. The left arm attaches the ORU to the node endcone, and once attached, both arms are released, the left arm stows TBD tool #2, and the SSRMS repositions the SPDM to close the m/d shields. After closing the m/d shields, the SSRMS repositions the SPDM to fasten the m/d shields; again the left arm is used for stabilization and the right arm unstows TBD tool #1 and fastens the debris shields. After fastening the shields the right arm stows tool #1 and the SPDM is placed back on the MSC by the SSRMS. The SSRMS then stows itself.

Assumptions:

1. The Space Station configuration is assembly complete.
2. The MSC has already translated with the SPDM and new ORU to the respective utility port near the changeout location.
3. The SPDM is attached to the SSRMS during ORU changeout operations.
4. Required tools are attached to the SPDM body. These tools are:
   - TBD allen wrench to unscrew the meteor debris (m/d) shields fasteners.
   - TBD tool to remove the TCS manifold; note: once this tool unbolts the ORU this attachment point can be used to grasp and transport the ORU.
5. The m/d shields are 42" x 84" x 0.5" curved plates and attached to the nodes by six 1/4 turn fasteners. To access the TCS manifold, the SPDM rotates the m/d shields about there hinged axis.
6. The SPDM can stabilize to the proposed node handholds and any additional handholds that must be at the worksite to make this task feasible.

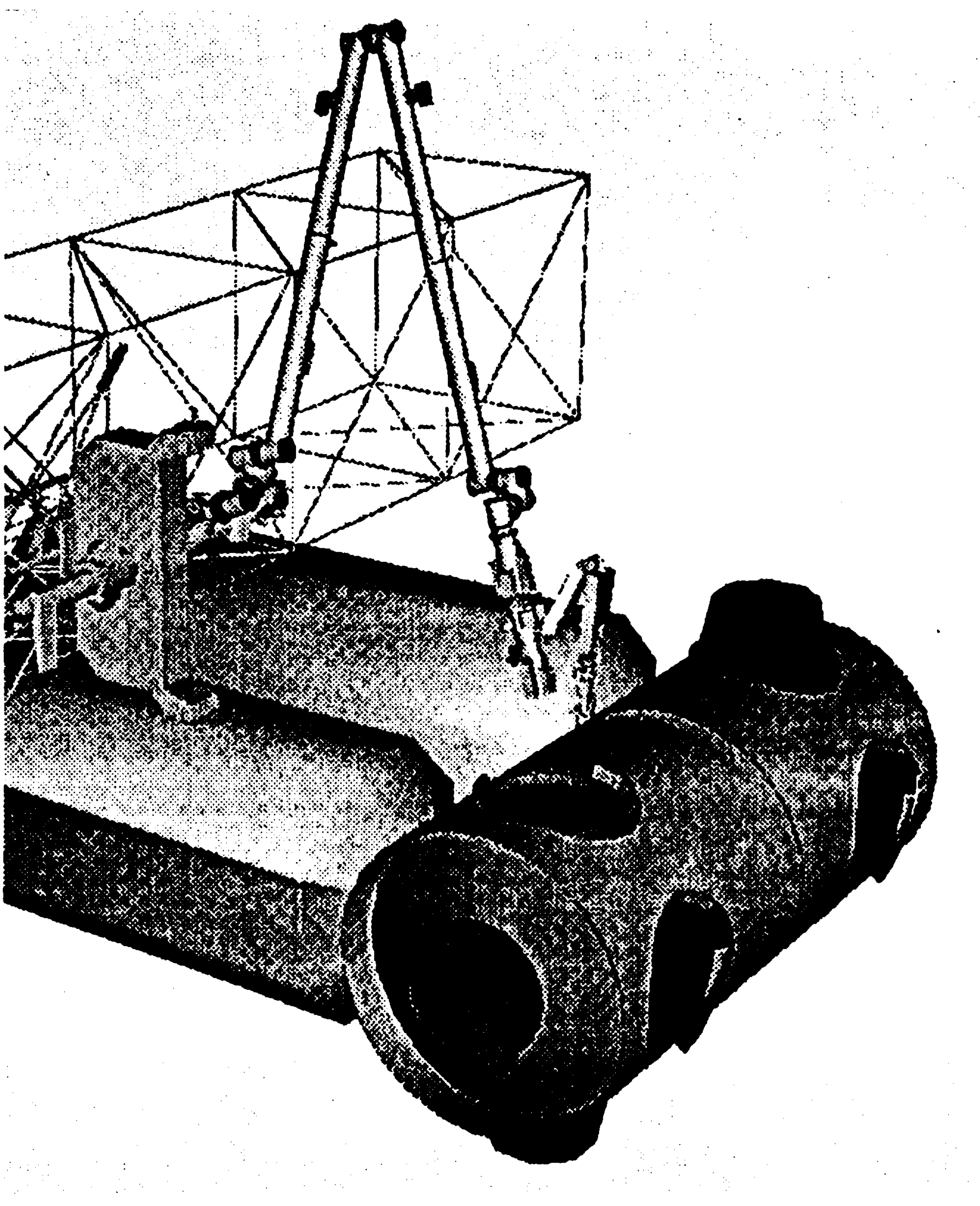


Figure H4-16. Debris Shield/TCS Manifold - SPDM

7. The TCS manifold interface is compatible with the Space Station node attachment location and the SPDM body storage locations.
8. The TCS manifold power, data and fluid lines are blind mate connectors and can be mated/demated when removing or installing the ORU with the SPDM.
9. The TCS manifold is attached to the endcone via two loadbearing connectors.

<u>Script</u>:

<u>H1</u> <u>SPDM removes old TCS manifold and installs new ORU</u>	<u>Time</u>
1. SSRMS executes auto-sequence to unstow, position and align end effector for grappling of SPDM.	1:20
2. SSRMS grapples and captures SPDM.	1:05
3. SPDM releases PDGF at location #6 and SSRMS positions SPDM near node end cones (see figure 1).	1:00
4. Unstow and position SPDM body for changeout operations.	1:05
5. Unstow, extend, and align left manipulator with m/d shield #1 node handhold for stabilization.	1:20
6. Left manipulator capture handhold to stabilize; calibrate and store orientation.	0:15
7. Right manipulator execute auto-sequence to unstow and retrieve TBD rotary tool.	1:30
8. Extend and align right end effector tool to unscrew fastener #1 on m/d shield #1 (see figure 2).	1:00
9. Capture fastener with right end effector tool and turn 1/4 turn to unscrew fastener.	0:25
10. Release and withdraw right end effector from fastener; extend and align end effector to unscrew fastener #2.	0:55
11. Capture fastener with right end effector tool and turn 1/4 turn to unscrew fastener.	0:25
12. Release and withdraw right end effector from fastener; extend and align end effector to unscrew fastener #4.	1:00
13. Capture fastener with right end effector tool and turn 1/4 turn to unscrew fastener.	0:25
14. Release and withdraw right end effector from fastener; extend and alignend effector to unscrew fastener #5.	1:05
15. Capture fastener with right end effector tool and turn 1/4 turn to unscrew fastener.	0:25

16. Release and withdraw right end effector from fastener. 0:07
17. Release and withdraw left end effector from handhold. 0:07
18. Reposition SPDM body with respect to the m/d shield by rotating 180 degrees to allow the right manipulator access to fasteners 3 & 6. 0:40
19. Extend and align left manipulator with mid shield #1 have handhold for stabilization. 1:00
20. Left manipulator capture handhold to stabilize; calibrate and store orientation. 0:25
21. Extend and align right end effector tool to unscrew fastener #6. 1:00
22. Capture fastener with right end effector tool and turn 1/4 turn to unscrew fastener. 0:25
23. Release and withdraw right end effector from fastener; extend and align end effector to unscrew fastener #3. 1:00
24. Capture fastener with right end effector tool and turn 1/4 turn to unscrew fastener. 0:25
25. Release and withdraw right end effector from fastener. 0:07
26. SSRMS executes auto-sequence maneuver to position SPDM to unscrew fasteners on m/d shield #2. 0:30
27. Reposition SPDM body for changeout operations. 0:20
28. Left manipulator capture handhold to stabilize; calibrate and store orientation. 0:15
29. Extend and align right end effector tool to unscrew fastener #1 on m/d shield #2. 1:00
30. Capture fastener with right end effector tool and turn 1/4 turn to unscrew fastener. 0:25
31. Release and withdraw right end effector from fastener; extend and align end effector to unscrew fastener #2. 0:55
32. Capture fastener with right end effector tool and turn 1/4 turn to unscrew fastener. 0:25
33. Release and withdraw right end effector from fastener; extend and align end effector to unscrew fastener #4. 1:00
34. Capture fastener with right end effector tool and turn 1/4 turn to unscrew fastener. 0:25
35. Release and withdraw right end effector from fastener; extend and align end effector to unscrew fastener #5. 1:05

36. Capture fastener with right end effector tool and turn 1/4 turn to unscrew fastener. 0:25

37. Release and withdraw right end effector from fastener. 0:07

38. Release and withdraw left end effector from handhold. 0:07

39. Reposition SPDM body with respect to the m/d shield #2 by rotating 180 degrees to allow the right manipulator access to fasteners 3 & 6. 0:40

40. Extend and align left manipulator with m/d shield #2 node handhold for stabilization. 1:00

41. Left manipulator capture handhold to stabilize; calibrate and store orientation. 0:25

42. Extend and align right end effector tool to unscrew fastener #6. 1:00

43. Capture fastener with right end effector tool and turn 1/4 turn to unscrew fastener. 0:25

44. Release and withdraw right end effector from fastener; extend and align end effector to unscrew fastener #3. 1:00

45. Capture fastener with right end effector tool and turn 1/4 turn to unscrew fastener. 0:25

46. Release and withdraw right end effector from fastener. 0:07

47. SSRMS executes auto-sequence maneuver to position SPDM to unhinge m/d shield #2. 0:20

48. Reposition SPDM body for m/d shield #2 opening operations. 0:45

49. Execute auto-sequence to allow right manipulator to stow TBD rotary tool to SPDM body. 1:30

50. Extend and align right manipulator with node handhold for stabilization. 1:00

51. Right manipulator capture handhold to stabilize; calibrate and store orientation. 0:25

52. Extend and align left manipulator with m/d shield #2 handhold for opening. 1:00

53. Left manipulator capture handhold and rotate door to open position. 0:50

54. Release and withdraw left end effector from handhold. 0:07

55. Release and withdraw right end effector from node handhold. 0:07

56. SSRMS executes auto-sequence maneuver to position SPDM to unhinge m/d shield #1. 0:20

57. Reposition SPDM body for m/d shield #1 opening operations. 0:15

58. Extend and align left manipulator with node handhold for stabilization. 1:00
59. Left manipulator capture handhold to stabilize; calibrate and store orientation. 0:25
60. Extend and align right manipulator with m/d shield #1 handhold for opening. 1:00
61. Right manipulator capture handhold and rotate door to open position. 0:50
62. Release and withdraw right end effector from handhold and position for the TCS manifold changeout. 1:50
63. Release and withdraw left end effector from handhold; execute auto-sequence to retrieve TBD rotary tool for removing the ORU. 1:30
64. SSRMS executes auto-sequence maneuver to position SPDM to allow better access to the ORU. 0:25
65. Extend and align right manipulator with node handhold for stabilization. 0:25
66. Right manipulator capture handhold to stabilize; calibrate and store orientation. 0:25
67. Extend and align the left end effector tool to remove the left load-bearing connector. 0:40
68. Capture connector and turn connector TBD turns to unscrew. 0:25
69. Release and withdraw left end effector from connector; extend and align end effector to unscrew the right load-bearing connector. 0:30
70. Capture connector and turn connector TBD turns to unscrew. 0:25
71. Withdraw left end effector and ORU away from node endcone and extendmanipulator to align the ORU with the SPDM base storage attachment location. 2:00
72. Attach TCS manifold to SPDM base; turn connector TBD turns to screw. 0:25
73. Release and withdraw right end effector from node handhold; extend and align end effector to new TCS manifold handhold. 1:50
74. Right manipulator capture handhold to remove ORU. 0:15
75. Withdraw right end effector and ORU away from SPDM base and extend manipulator to handoff ORU to left manipulator. 1:00
76. Release and withdraw left end effector from old TCS manifold connector; extend and align end effector to new TCS manifold load bearing connector. 2:00

77.	Right manipulator capture connector.	0:25
78.	Release and withdraw right end effector from ORU; extend and align right manipulator with node handhold for stabilization.	1:25
79.	Right manipulator capture handhold to stabilize; calibrate and store orientation.	0:25
80.	Extend and align left end effector and ORU at node attachment location.	1:20
81.	Attach TCS manifold to endcone and turn load bearing connector TBD turns to connect to endcone.	0:25
82.	Release connector; extend and align the left end effector tool to remove the left load bearing connector.	0:40
83.	Capture connector and turn connector TBD turns to unscrew.	0:25
84.	Release and withdraw left end effector from connector.	0:20
85.	Release and withdraw right end effector away from node handhold.	0:20
86.	Standby for functional test and inspect repair site.	1:00
87.	Execute auto-sequence to allow left manipulator to attach TBD tool to the SPDM body.	1:30
88.	Repeat steps 50-64 in reverse order to allow the SPDM to close debris shields 1 and 2.	11:04
89.	Repeat steps 5-49 in reverse order to allow the SPDM to fasten debris shields 1 and 2.	27:37
90.	Inspect shield placement and worksite area.	1:00
91.	Execute auto-sequence to stow SPDM body and both manipulators.	3:00
92.	SSRMS executes auto-sequence to position and align SPDM to MSC storage location.	1:00
93.	SPDM grapples PDGF and SSRMS ungrapples SPDM.	1:00
95.	SSRMS executes stow auto-sequence	1:00
	Total	106 min 45 sec

Changeout of SPDM Computer ORU by FTS

Synopsis:

The Flight Telerobotic Servicer (FTS) replaces an electrical system ORU box on the SPDM lower body segment. The procedure takes place on the MRS with the FTS at its storage location. The SPDM is located on PDGF 2, putting it within reach of the FTS manipulators.

Assumptions:

1. FTS has power/data/video available through a WAF/WAM combination at the storage location on the MRS.
2. SPDM body mechanisms remain functional when arms are not.
3. SPDM ORU interfaces are compatible with FTS tools.
4. FTS can position its body through motion of ASPS while ASPS is attached to WAF.
5. FTS begins procedure with replacement ORU grappled to right arm which is positioned out of the workspace.
6. Replacement ORU is stored on MMD.
7. SPDM ORU can be blind mated to SPDM body.
8. SPDM ORU dimensions are zero to one inch less than maximum envelope dimensions provided by SPAR.
9. ORU interface consists of two H-handle bolt heads.
10. FTS joint rate limit is five degrees/second. Tip velocity is two feet/second, unloaded.
11. SPDM failed ORU located on SPDM lower body.
12. Stowed SPDM arms do not interfere.
13. SPDM can be left in stowed position for changeout.

Concerns:

1. If SPDM cannot be relocated from its storage location on PDGF 4, there is no place to attach the FTS ASPS so that FTS can reach SPDM.
2. Storage locations of ORUs on MRS are still undefined. A possible solution is to bring the ULC holding the ORUs along on the task by placing it on a POA. This also eliminates the need to operate FTS or SPDM for ORU retrieval before arriving at the worksite, a substantial time savings.
3. SPDM ORU dimensions, mass properties, robot interfaces, and alignment/targeting aids are undefined.
4. FTS/SPDM EE cameras are not the same distance from the robot's end effector on wrist centerline. Therefore an alignment/targeting guide designed for one robot could not be used by the other.

Script for changeout of SPDM ORU.

1. Unstow SSRMS
2. Translate SSRMS to SPDM storage location.

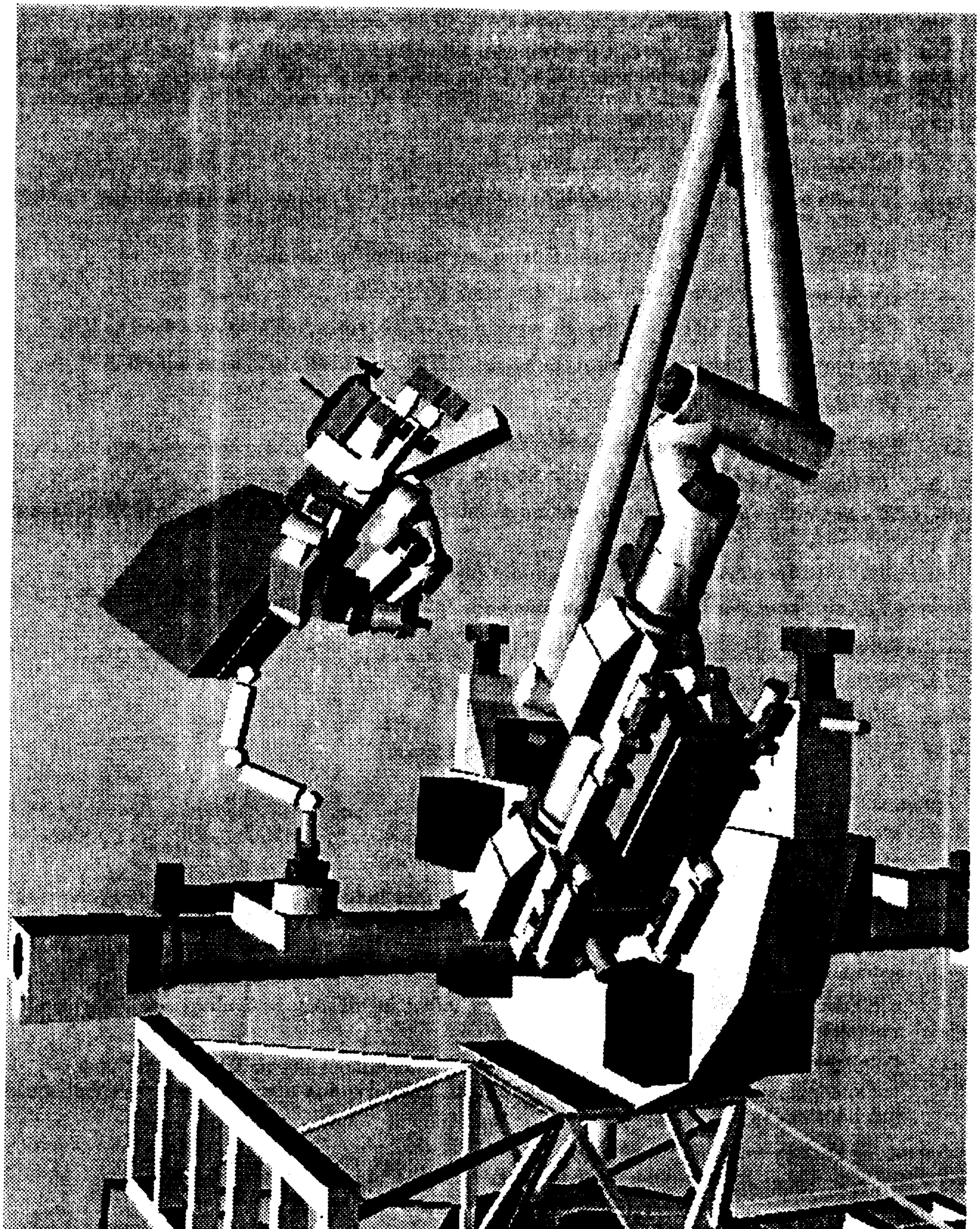


Figure H4-17. SPDM/ORU - Changeout - FTS

3. Align SSRMS with SPDM.
4. Grapple SPDM.
5. Release SPDM from PDGF 4.
6. Extend SSRMS with SPDM to PDGF 2.
7. Align SPDM base with PDGF 2.
8. Grapple PDGF 2 with SPDM latching end effector.
9. Maneuver SPDM body joints to expose failed ORU.
10. Maneuver FTS ASPS to position FTS body facing SPDM.

******************** Begin timing **********************

11.	Extend right arm to first end effector interface.	0:50
12.	Align right arm end effector with first interface.	1:52
13.	Grapple first interface.	
14.	Unlock first interface.	
15.	Withdraw right end effector.	0:15
16.	Extend right arm to second end effector interface.	0:21
17.	Align right end effector to second interface.	1:59
18.	Grapple second interface.	
19.	Unlock second interface.	
20.	Withdraw right arm (with old ORU) out of workspace.	2:34
21.	Drive left arm in Single Joint mode to bring arm/ORU into workspace.	1:55
22.	Extend left arm (with new ORU) to vacant ORU slot.	1:18
23.	Align new ORU with left arm.	0:23
24.	Insert new ORU.	
25.	Lock end effector interface with left end effector.	
26.	Withdraw left end effector.	0:07
27.	Extend left end effector to second interface.	0:14
28.	Align left end effector to second interface.	2:03
29.	Insert left end effector into second interface.	0:29
30.	Grapple second interface.	
31.	Lock second interface down with left end effector.	
32.	Withdraw left end effector.	0:11

********************End Timing*************************

	Total	14:31 min

Script for Changeout of Beta Gimbal Subassembly using the Flight Telerobotic Servicer (FTS)

Synopsis:

The gear and bearing subassembly, located in the beta gimbal, is replaced by the FTS. The FTS is supported by the SSRMS with the ASPS attached to the CETA rail for stabilization. The right arm holds the replacement ORU whitle the left arm removes the expended ORU.

Assumptions:

1. The timeline begins with the FTS captured by the SSRMS and the replacement ORU captured by the right arm.
2. The ASPS has a gripper as an end effector that is capable of grappling any handle that is structurally strong enough. In this case, it is assumed that there is an EVA type handhold on the CETA rail directly beneath the beta gimbal on which the ASPS can stabilize. There is no power, data, or video through this connection.
3. Left and right arm have 6-DOF active control, shoulder roll is indexed.
4. SSF coordinate origin for this task is at the center of the truss bay below the beta gimbal and the axes are parallel to the accepted SSF coordinate system (+X out front face, +Z to Earth, +Y out the starboard side).
5. The left arm performs both removal and insertion of the ORUs since the diagonal truss beam below the beta gimbal limits the range of motion of the right arm. The ex pended and replacement ORUs are, therefore, juggled between the left and right arms and the ASPS while the FTS is out of the truss bay between removal and insertion of the ORUs. This juggling necessitates two handles on each ORU.
6. Both the left and right arm are using the multi-purpose parallel jaw gripper as an end effector.
7. The beta gimbal involved in the changeout is on bay SA2. The utility port for the MSC is on the foreward face of the same bay.
8. The handles on the gear and bearing subassembly can be arbitrarily placed so as to make the task as simple as possible for the robot to perform.

Concerns:

1. The diameter of the beta gimbal housing subassembly (21.02 inches) is only slightly larger than that of the gear and bearing subassembly (20.59 inches). This means that during removal and insertion of the ORU, there is very little room for error. To successfully complete the task, the left arm of the FTS must be able to work at this degree of accuracy. Also, extremely precise alignment guides must be implemented to ensure that insertion occurs with the ORU in exactly the right position.
2. There is only 30.5 inches between the bottom of the beta gimbal housing subassembly and the CETA rail and diagonal truss beam. The ORU is approximately 20 inches long. Therefore, the robot has only 10.5 inches of spare space during the removal and insertion portions of this task.
3. The robot must move very precisely while manuvering within the truss bay to avoid collisions with the truss structure, the CETA rail, and the transition struts. The magnitude of this problem is increased when the arm is moving the ORU in this space.

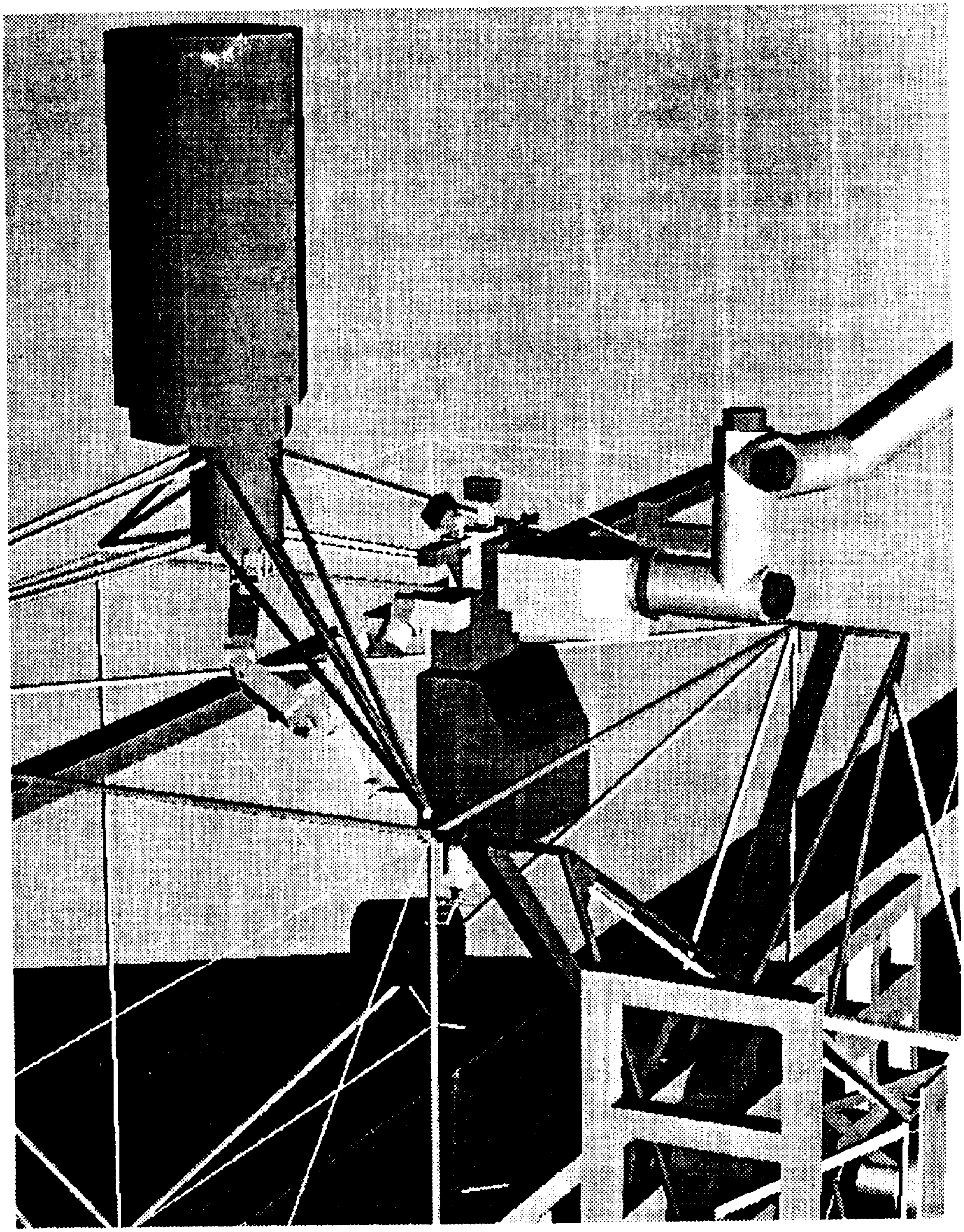


Figure H4-18. Beta Gimbal Changeout - FTS

Script:

FTS removes/installs ORU.

1. SSRMS positions FTS to worksite.
2. Extend ASPS end effector to stabilization interface point on CETA rail.
3. Align ASPS end effector for grappling onto stabilization interface.
4. Grapple stabilization point with ASPS end effector.
5. Extend left end effector to old ORU end effector interface.
6. Align left end effector to old ORU end effector interface.
7. Capture old ORU end effector interface with left end effector.

***************** Begin Timing********************

8. Rotate ORU with left arm in Payload mode 20 degrees about SSF +Z (YAW) to unlock ORU. 0:25
9. Translate old ORU in SSF +Z with left arm in Payload mode to clear beta gimbal housing. 0:30
10. Translate and Rotate old ORU in closer to FTS body to clear surrounding trus beams and transition struts. 2:55
11. Ungrapple ASPS end effector.
12. Stow ASPS. 1:20
13. Translate FTS out of truss bay with SSRMS. 1:40
14. Translate left arm to handoff old ORU to ASPS. 5:00
15. Extend ASPS to grapple second handle on old ORU. 2:35
16. Align gripper on ASPS with second handle on old ORU. 2:00
17. Capture old ORU second handle with ASPS gripper.
18. Release old ORU from gripper on left hand.
19. Withdraw left hand from workspace. 1:30
20. Extend ASPS down and out of the two arms workspace. 3:45
21. Extend right arm with new ORU into the workspace of the left arm. 7:25
22. Extend left arm end effector to new ORU end effector interface. 2:00
23. Align left arm end effector to new ORU end effector interface. 2:35
24. Grapple new ORU end effector interface with left arm end effector.
25. Release new ORU second handle with right arm.
26. Extend right arm away from above ASPS. 1:00
27. Extend left arm out of rigjt arm's workspace 2:00
28. Extend ASPS with old ORU into right arm's workspace. 5:10

29.	Extend right arm end effector to end effector interface on old ORU.	1:10
30.	Align right arm end effector to old ORU end effector interface.	2:00
31.	Capture old ORU end effector interface with right arm end effector.	
32.	Release old ORU from ASPS	
33.	Stow ASPS.	1:20
34.	Extend right arm with old ORU to its stowed position:	6:30
35.	Extend left arm with new ORU in close to FTS' chest.	11:00
36.	Reposition SSRMS with FTS back into truss bay in previous position.	2:35
37.	Extend ASPS end effector to stabilization interface point on CETA rail.	6:55
38.	Align ASPS end effector for grappling onto stabilization interface.	
39.	Grapple stabilization point with ASPS end effector.	
40.	Extend left arm with new ORU to insertion position under beta gimbal.	2:05
41.	Translate new ORU in SSF -Z with left arm in Payload mode until insertion of subassembly into beta gimbal housing is complete.	0:25
42.	Rotate ORU with left arm in Payload mode 20 degrees about SSF -Z (YAW) to lock ORU	0:25
43.	Ungrapple new ORU with left end effector.	

************************End Timing*********

Total	76:15 min

44. Stow left arm.
45. Translate FTS out of truss bay with SSRMS.

Recommendations:

GSFC suggested that instead of entering the truss bay from the top, between the transition struts, FTS could enter from the back of the truss bay and work facing the bottom of the beta gimbal from beneath the CETA rail. Although this method would lessen the interference of the transition struts, it would increase the problem of manuvering around the CETA rail and diagonal truss beam. Also, the entire SSRMS wrist would need to be inserted into the truss bay, as opposed to just the body of the FTS.

Script for Changeout of Beta Gimbal Subassembly using the Special Purpose Dextrous Manipulator (SPDM)

Synopsis:

The gear and bearing subassembly, located in the beta gimbal, is replaced by SPDM. SPDM is supported by the SSRMS through the changeout. The left arm is attached to the CETA rail for stabilization during the removal and insertion of the ORUs. The replacement ORU is stored at the ORU standoff at the base of the SPDM.

Assumptions:

1. The timeline begins with SPDM capture by the SSRMS, the replacement ORU stowed on the SPDM base, the left arm grappled to the CETA rail, and the right arm grappled to the old ORU.
2. SSF coordinates for this task are centered at the center of the truss bay below the beta gimbal and line up with accepted SSF coordinate system (+X out front face, +Z to Earth, +Y out the starboard side).
3. Both the left and right arm are using the multi-purpose parallel jaw gripper as an end effector.
4. The ORU's can be secured to the ORU standoffs located at the base of SPDM.
5. The ORU's can be secured to and removed from the ORU standoffs while SPDM is being supported by the SSRMS without additional stabilization.
6. An interface exists on the CETA rail which the left arm of the SPDM can grapple.

Concerns:

See concerns section of beta gimbal changeout using FTS.

Script:

SPDM removes/installs ORU.

1. SSRMS positions SPDM to worksite inside of truss bay.
2. Extend left end effector to stabilization interface point.
3. Align left end effector for grappling onto stabilization interface.
4. Grapple stabilization point with left end effector.
5. Extend right end effector to old ORU end effector interface.
6. Align right end effector to old ORU end effector interface.
7. Capture old ORU end effector interface with right end effector.

***************** Begin Timing *********************

8. Rotate ORU with right arm in Payload mode 20 degrees about SSF +Z (YAW) to unlock ORU	0:20
9. Translate old ORU in SSF +Z with right arm in Payload mode clear of beta gimbal housing.	0:46
10. Translate and Rotate old ORU in closer to SPDM body to clear surrounding truss beams and transition struts.	1:02

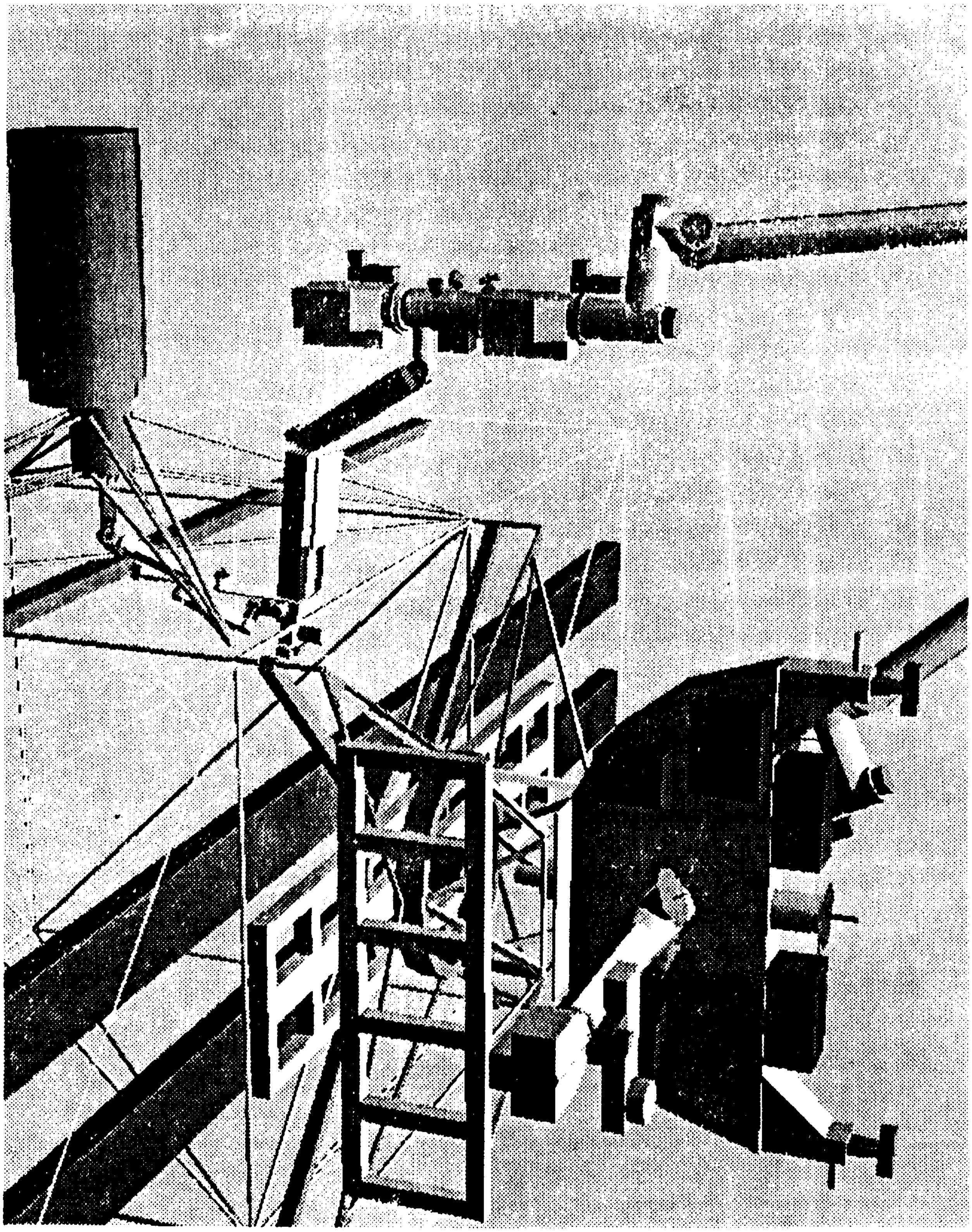


Figure H4-19. Beta Gimbal Changeout - SPDM

11. Ungrapple left end effector.
12. Stow left arm. 0:37
13. Translate SPDM out of truss bay with SSRMS. 2:13
14. Extend body in Single Joint mode so that old ORU stowage location on SPDM base is in workspace of right arm. 3:47
15. Translate right arm to stow old ORU to SPDM base. 4:00
16. Align old ORU with right arm to stowage location.
17. Stow old ORU on SPDM base stowage location.
18. Release old ORU from gripper on right hand.
19. Withdraw right are from old ORU. 0:33
20. Move body to the other side of SPDM base so that second ORU standoff structure is in arm's workspace. 4:00
21. Extend right arm to new ORU end effector interface. 3:15
22. Align right arm end effector to new ORU end effector interface.
23. Grapple new ORU end effector interface with right arm end effector.
24. Remove new ORU from SPDM base stowage location. 0:18
25. Move body for insertion into truss bag. 3:47
26. Extend right arm with new ORU in close to SPDM's chest. 8:15
27. Reposition SSRMS with SPDM back into truss bay in previous position. 2:10
28. Extend left end effector to stabilization interface point on CETA rail. 2:13
29. Align left end effector for grappling onto stabilization interface.
30. Grapple stabilization point with left end effector.
31. Extend right arm with new ORU to insertion position under beta gimbal. 2:22
32. Translate new ORU in SSF -Z with right arm in Payload mode until insertion of subassembly into beta gimbal housing is complete. 0:21
33. Rotate ORU with right arm in Payload mode 20 degrees about SSF -Z (YAW) to lock ORU. 0:49
34. Ungrapple new ORU with right end effector.

************************End Timing************

Total 62:00 min

35. Stow both arms.
36. Translate SPDM out of truss bay with SSRMS.

Recommendations:

1. Spar suggested performing the task with the SPDM positioned outside of the transition struts with one arm attached to a truss node for stabilization and the other one manuvering the ORU. In this scenario, the body of the robot does not enter the truss bay. Some reach and clearance analysis would have to be performed for this scenario since it was not simulated in this study.
2. SPAR also suggested that the transition struts could be lengthened, thus increasing the space in which the robot has to work.

Script for Changeout of Battery Orbital Replacement Unit (ORU) on the Mobile Transporter (MT) using the Flight Telerobotic Servicer (FTS)

Synopsis:

An MT battery is replaced by the FTS. The FTS is supported by the SSRMS during the changeout. The ASPS is attached to a truss node during removal and insertion of the battery. The right arm holds the replacement ORU.

Assumptions:

1. Section H. of the end-to-end timeline begins with FTS capture by the SSRMS, the replacement ORU capture by the right arm, and the left arm poised above the old ORU.
2. The FTS will be stabilized using the ASPS attached to an SSF truss bay node using the Node Attachment Tool (NAT).
3. The FTS will be using its gripper tool. The ORU end effector interface will be compatible with the gripper. The fingers will capture the payload before the bolt is activated with the gripper's built-in rotary drive tool interface in the "palm" of the gripper. If the gripper needs the rotary tool held between the fingers for bolt activation, then it is assumed that the ORU is automatically captured by the rotary tool before bolt activation.
4. Rate hand controllers were used on the Multi-Manipulator Crew Workstation. Joint rate limit for FTS was 5 deg/sec.
5. The interface between the batteries and the MT is not known. The batteries are assumed to be connected to the MT only by the attachment rods on each end of the batteries.
6. There is no structure surrounding the batteries except for the other batteries and the MT. Therefore, the battery can be removed from its original position in any manner that avoids these objects.
7. Some sort of alignment guides exist for positioning the new ORU in place.
8. The FTS does not need to be stabilized when screwing in secondary bolts.

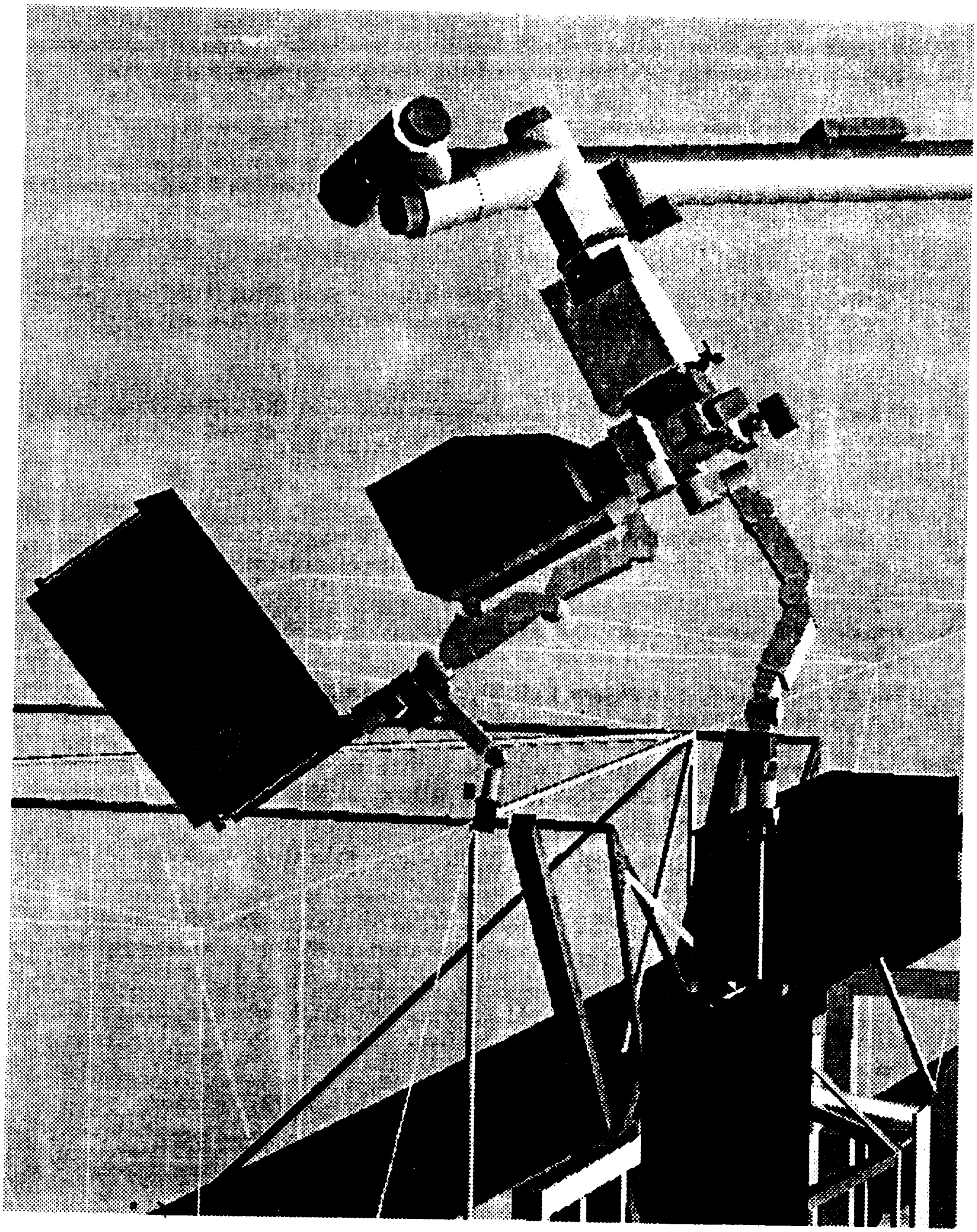


Figure H4-20. MT Battery Changeout - FTS

Concerns:

The left arm can not withdraw the battery straight out of its original position due to joint limits in the arm. Approximately 1/3 of the battery can be withdrawn using only translational motion. Then rotational motion must be used to completely withdraw the battery. This could be a problem if the structure which is holding the batteries in place interferes. This problem could be alleviated if the SSRMS repositions the FTS after the left arm of the FTS has captured the old ORU. This would add time to the task, but the task could still be done by the robot.

Script:

H. FTS removes/installs ORU.

1. SSRMS positions FTS to worksite.
2. Extend ASPS NAT to truss node located near old ORU.
3. Align ASPS NAT for insertion into truss node.
4. Insert ASPS NAT into truss node.
5. Extend left end effector to old ORU first end effector interface
6. Align left end effector for insertion into end effector interface
7. Insert left end effector into interface.
8. Left gripper rotary tool interface unscrews bolt.

******************** Begin Timing ****************

9.	Left end effector withdraws from interface.	0:10
10.	Extend left end effector to second end effector interface.	0:40
11.	Align left end effector for insertion into second interface.	2:02
12.	Insert left end effector into second	
13.	Left end effector rotary tool unscrews bolt.	
14.	Withdraw left end effector (with old ORU) clear of adjacent ORUs and clear of workspace.	2:11
15.	Right arm extends end effector (with new ORU) to empty ORU slot.	8:38
16.	Right end effector orients new ORU above empty ORU slot.	1:05
17.	Right end effector inserts new ORU into empty ORU slot.	
18.	Right end effector rotary tool screws down first bolt.	
19.	Right end effector withdraws from first end effector interface.	0:05
20.	Withdraw ASPS from stabilization position.	
21.	Stow ASPS.	0:40
22.	Reposition FTS using SSRMS so that right arm can easily grapple second interface point.	0:50
23.	Extend right end effector to second end effector interface.	1:15

24. Align right end effector for insertion into second end effector interface. 0:30
25. Insert right end effector into second end effector interface.
26. Right end effector rotary tool screws down second bolt.
27. Right arm withdraws from second end effector interface.

****************End Timing***************

Total 16:2 min

28. Right arm stows.
29. SSRMS positions FTS away from worksite.

Script for Changeout of Battery Orbital Replacement Unit (ORU) on the Mobile Transporter (MT) using the Special Purpose Dextrous Manipulator (SPDM)

Synopsis:

An MT battery is replaced by SPDM. SPDM remains on its base on the MRS throughout the changeout. The right arm holds the replacement ORU.

Assumptions:

1. The timeline begins with the SPDM base latching end effector attached to PDGF 6 on the MRS, the replacement ORU captured by the right arm, and the left arm poised above the old ORU.
2. The SPDM will be using Flight Telerobotic Servicer (FTS) multi-purpose parallel jaw gripper tool since a gripper tool for the SPDM is currently undefined. The ORU end effector interface will be compatible with the gripper. The fingers will capture the payload before the bolt is activated with the gripper's built in rotary drive tool interface in the "palm" of the gripper. If the gripper needs the rotary tool held between the fingers for bolt activation, then it is assumed that the ORU is automatically captured by the rotary tool before bolt activation.
3. Rate hand controllers were used on the Multi-Manipulator Crew Workstation. Joint rate limit for SPDM is 5 deg/sec.
4. The replacement ORU is stowed on the ULC which is attached at the POA on the same side of the MRS as PDGF 6.
5. The interface between the batteries and the MT is not known. The batteries are assumed to be connected to the MT only by the attachment rods on each end of the batteries.
6. There is no structure surrounding the batteries except for the other batteries and the MT. Therefore, the battery can be removed from its original position in any manner that avoids these objects.
7. Some sort of alignment guides exist for positioning the new ORU in place.
8. The SPDM does not need to be stabilized when screwing in secondary bolts.

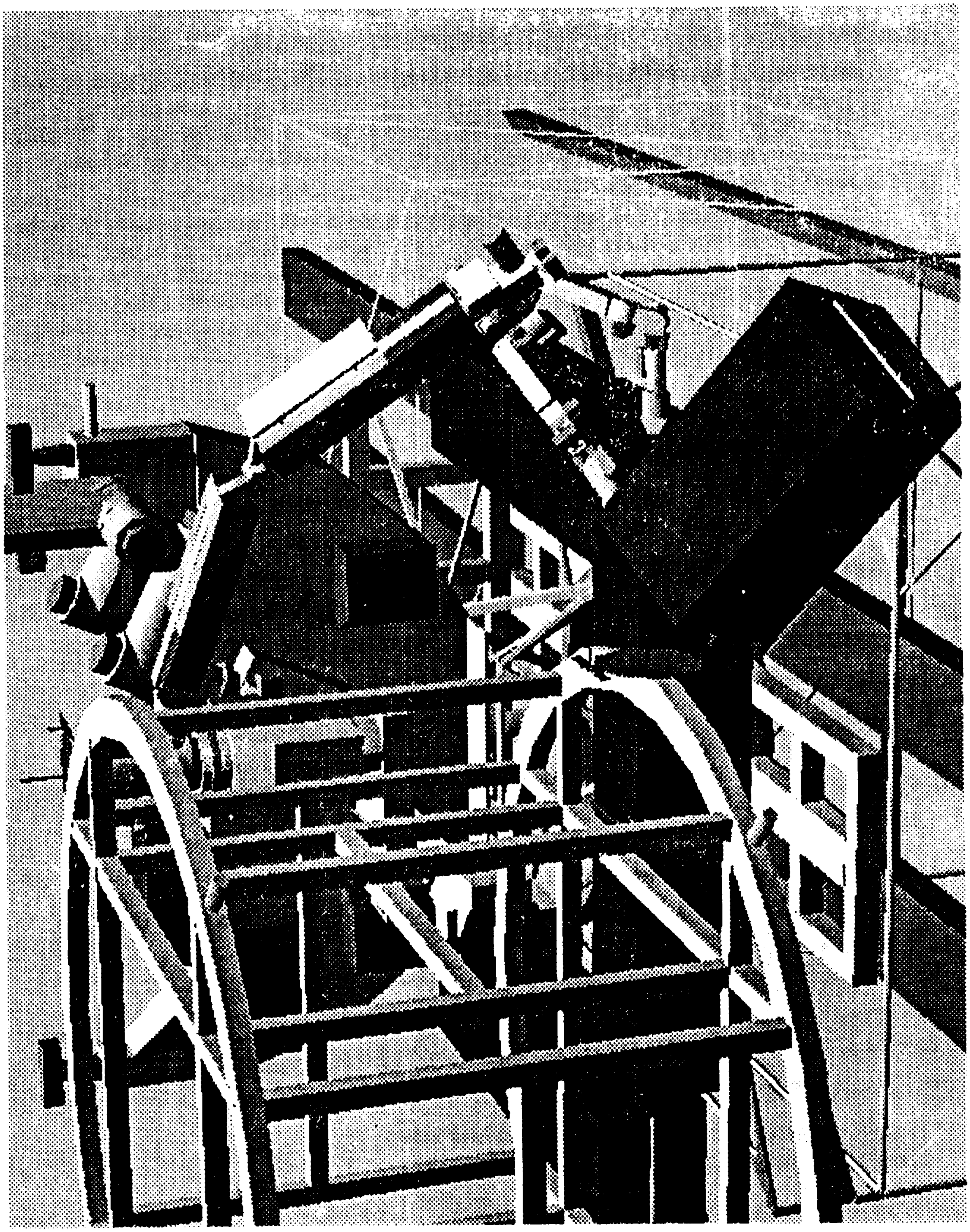


Figure H4-21. MT Battery Changeout - SPDM

Concerns:

1. The concern discussed for the battery changeout using the FTS is also encountered with the SPDM. Without repositioning the body of SPDM, approximately half of the ORU could be withdrawn in a translation only motion. Moving the body of SPDM in single joint mode while maintaining this translation motion would be difficult.

2. SPDM could not reach all six of the MT batteries from PDGF 6. Therefore, to remove some of the batteries, it might be necessary to move SPDM to the worksite with the SSRMS as was done in the case using the FTS. However, if this were done, the right arm would be needed for stabilization and, therefore, could not hold the replacement ORU. The replacement ORU could be placed on the ORU standoff located on the base of SPDM. The left arm could then remove the old ORU, place it on the empty ORU standoff, get the new ORU from the other ORU standoff and position it in the battery configuration.

Script:

SPDM removes/installs ORU.

1. SPDM body unstows and extends arms toward ULC.
2. SPDM body orients so right arm can easily capture new ORU stowed on ULC.
3. Right arm extends end effector toward new ORU
4. Right end effector aligns with first end effector interface on new ORU.
5. Right end effector aligns to interface.
6. Insert right end effector into interface.
7. Right end effector unscrews first interface.
8. Right arm withdraws end effector and extends toward second interface.
9. Right arm aligns end effector to second interface.
10. Insert end effector into interface.
11. Right end effector unscrews interface.
12. Right arm withdraws end effector (with new ORU) and positions it out of SPDM workspace.
13. SPDM body positions arms to workspace above old ORU.
14. Extend left end effector to old ORU first end effector interface
15 Align left end effector for insertion into end effector interface
16 Insert left end effector into interface.
17. Left gripper rotary tool interface unscrews bolt.

******************** Begun Timing ****************

18. Left end effector withdraws from interface. 0:13
19. SPDM body orients left arm for easy access to second end effector interface. 1:00

20.	Extend left end effector to second end effector interface.	0:45
21.	Align left end effector for insertion into second interface.	1:34
22.	Insert left end effector into second end effector interface.	1:33
23.	Left end effector rotary tool unscrews bolt.	
24.	Withdraw left end effector (with old ORU) from adjacent ORU's.	1:25
25.	SPDM body orients left arm (with old ORU) away from adjacent ORU's	0:53
26.	Stow left arm (with old ORU).	2:45
27.	Right arm extends end effector (with new ORU) to empty ORU slot.	8:41
28.	Right end effector orients new ORU above empty ORU slot.	0:09
29.	Right end effector inserts new ORU into empty ORU slot.	
30.	Right end effector rotary tool screws down first bolt.	
31.	Right end effector withdraws from first end effector interface.	0:20
32.	SPDM body reorients right arm so it can easily grapple second interface point.	1:20
33.	Extend right end effector to second end effector interface.	5:00
34.	Align right end effector for insertion into second end effector interface.	1:45
35.	Insert right end effector into second end effector interface.	
36.	Right end effector rotary tool screws down second bolt.	
37.	Right arm withdraws from second end effector interface.	

*****************End Timing*************

Total	27.23 min

Changeout of the Orbital Replacement Unit (ORU) on the Integrated Equipment Assembly (IEA) using the Flight Telerobotic Servicer (FTS) (Teleoperations Method)

Synopsis:

In this task, the FTS will first be captured by the Space Station Remote Manipulator (SSRMS), which is mounted on the Mobile Servicing Center (MCS), and moved inside the truss over the ORU needing to be replaced on the IEA. The FTS will then stabilize and disconnect the expanded ORU. The FTS then releases the IEA worksite and is moved by the SSRMS to the dry cargo sub-carrier on the MSC carring the expended ORU. The FTS stows the expended ORU and retrieves a replacement from the dry cargo subcarrier. The SSRMS again, moves the FTS to The IEA worksite. The replacement ORU is connected, and the FTS stows itself, is withdrawn from the truss, and transported back to the Mobile Servicing Center (MSC) by the SSRMS. The times indicated in the following script represent maintenance by teleoperations.

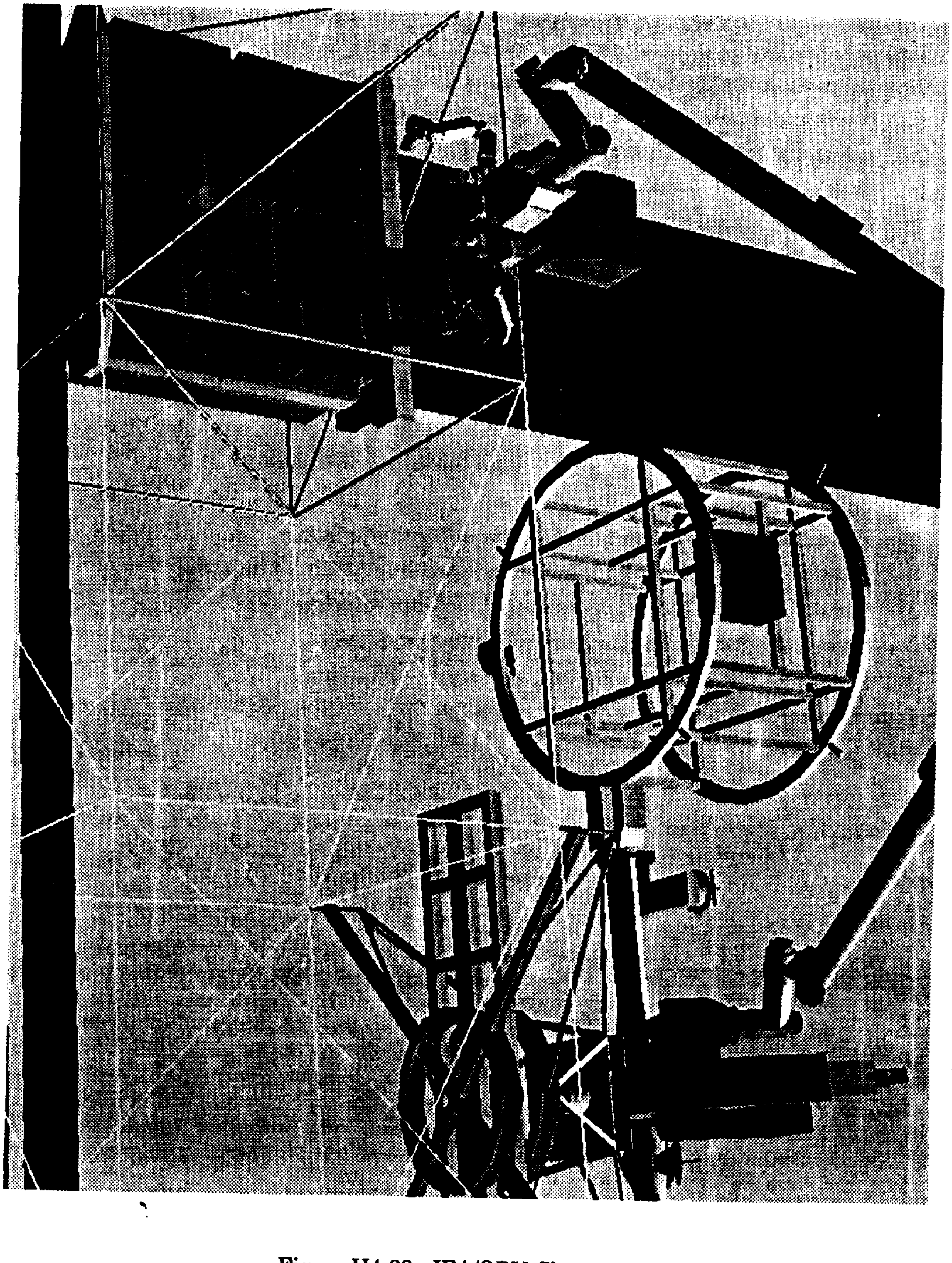


Figure H4-22. IEA/ORU Changeout

Assumptions:

1. The FTS performs the ORU exchange while attached to the Space Station Remote Manipulator System (SSRMS) end effector.
2. FTS uses two (2) User-Provided Tools (UPT).
3. Auto-sequence/trajectories will be utilized where sufficiently accurate positional information exists.
4. Visual targets exist on the UPT interfaces.
5. ORU structural interface and the UPT stabilization are the same.
6. Replenishment and expended ORUs are sufficiently attached to the ORU location on the Mobile Service Center (MSC) by a single structural interface bolt.
7. All auto-sequences will be joint angle trajectorises not POR trajectories.
8. FTS Attachment, Stabilization and Positioning Subsystem (ASPS) are not used for the ORU exhange.

Script:

H1. FTS removes/installs IEA ORU	Time
1. Unstow SSRMS and extend to FTS	1:45
2. Align SSRMS for grapple of FTS	3:04
3. SSRMS manually grapples FTS.	0.06
4. FTS ASPS releases Worksite Attach Fixture (WAF)/PDGF location #8.	
5. SSRMS positions FTS outside of truss bay above worksite.	11:32
6. Unstow left arm with UPT attached	11:02
7. Unstow right arm with UPT attached.	5:03
8. Stow ASPS.	2:28
9. Position SSRMS elbow camera for operation viewing.	1:32
10. Position FTS head cameras for operational viewing.	0:38
11. SSRMS positions FTS at worksite inside truss bay.	17:10
12. Extend left arm to frst stabilization interface point.	0:45
13. Align left UPT for insertion into first stabilization interface point.	3:55
14. Extend right arm to first structure interface of old ORU.	3:17
15. Align right UPT to insert into first structural interface of old ORU.	10:13
16. Unbolt old ORU's first structural interface with right UPT.	
17. Release old ORU.	
18. Withdraw right UPT from ORU's first structural interface.	1:43
19. Extend right UPT to second UPT stabilization interface point.	0:11
20. Align right UPT to second UPT stabilization interface point.	0:31
21. Manually insert right UPT into second UPT stabilization interface point.	

22. Detach left UPT from first UPT stabilization interface point.	
23. Withdraw left UPT from first UPT stabilization interface.	0:33
24. Extend left UPT to old ORU's second structural interface point.	1:57
25. Align left UPT for insertion into old ORU's second structural interface point.	
26. Manually insert left UPT into second structural interface of old ORU.	
27. Unbolt old ORU's second structural interface with left UPT.	
28. Withdraw left UPT with old ORU attached.	3:20
29. Detach right UPT from second UPT stabilization interface point.	
30. Withdraw right UPT from second UPT stabilization interface.	1:10
31. Stow right arm.	1:50
32. SSRMS withdraws FTS from worksite position.	4:00
33. SSRMS positions FTS with ORU to ULC storage location.	4:00
34. Position SSRMS elbow camera for operation viewing	2:02
35. Position FTS head cameras for operational viewing.	0:45
36. Extend and align right UPT to ULC stabilization interface point.	0:45
37. Manually insert right UPT into ULC stabilization interface.	
38. Extend old ORU to ULC storage location.	7:38
39. Align old ORU for insertion into ULC storage location.	15:02
40. Manually insert old ORU into ULC storage location.	
41. Bolt old ORU's first structural interface with left UPT.	
42. Release old ORU.	
43. Withdraw left UPT from ORU's second structural interface.	0:30
44. Extend left UPT to location of new ORU's second structural interface point.	1:40
45. Align left UPT for insertion into new ORU's second structural interface point.	6:47
46. Insert left UPT into new ORU's second structural interface point.	
47. Unbolt new ORU's second structural interfaces with left UPT.	
48. Withdraw new ORU from stowed location.	3:13
49. SSRMS withdraws FTS from ULC.	10:20
50. SSRMS positions FTS at worksite.	3:01
51. Position SSRMS elbow camera for operation viewing.	0:30
52. Position FTS head cameras for operational viewing.	7:48
53. Extend right UPT to second UPT stabilization interface point.	1:14

54. Aligh right UPT for insertion into second UPT stabilizaiton interface point.	3:05
55. Manually insert right UPT into second UPT stabilization interface.	
56. Extend new ORU to empty ORU slot.	0:30
57. Align new ORU for insertion into empty ORU slot.	
58. Manually insert new ORU into ORU interface.	3:38
59. Bolt new ORU into second structural interface with left UPT.	
60. Release new ORU.	
61. Extend left UPT to first UPT stabilization interface point.	
62. Align left UPT for insertion into first UPT stabilization interface point.	
63. Insert left UPT into first UPT stabilization interface point.	0:51
64a. Detach right UPT from second UPT stabilization interface point.	
64b. Withdraw right UPT from second UPT stabilization interface	0:10
65. Extend right UPT to new ORU's first structural interface point.	
66. Align right UPT for insertion into new ORU's first structural interface point.	
67. Insert right UPT into replenishment ORU's first structural interface.	0:24
68. Bolt new ORU's into first structural interface with right UPT.	
69. Withdraw right UPT from ORU's first structural interface.	0:25
70. Stow right Arm.	5:03
71. Detach left UPT from first UPT stabilization interface point.	
72. Withdraw left UPT from first UPT stabilization interface.	
73. Stow left arm.	11:02
74. Standby for new ORU checkout.	
75. SSRMS positions FTS for stow on MSC WAF/PDGF location #8.	12:05
76. Manually stow of FTS on MSC WAF/PDGF location #8.	1:37
77. FTS ASPS capture of MSC WAF/PDGF location #8.	3:00
78. SSRMS releases FTS.	0:35
79. Manual SSRMS stow.	6:05

*******************End Timing*****

Total	201:10 min

Acknowledgments

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31459E313 ICD SPDM Electronics Placement

31459E412 Assembly Special Purpose Dexterous Manipulator

31459D121 Assembly SPDM ARM 7DOF with Non-Redundant Joints

MRS Drawing, SPAR Aerospace

31459E171 MSC/SPDM On ORbit Configuration MSS

31459E249 POA Support Assembly #1

31459E250 POA Support Assembly #2

31459E375 MBS/MRS Electrical Systems

31459E438 MBS Base Structure

The Effect of Robot Autonomy on Crew Time Required for Maintenance of Space Station Freedom

Appendix H5

July 1990

The Effect of Robot Autonomy on Crew Time Required for Maintenance of Space Station Freedom

Summary

Because of the large scope of maintenance required on Space Station Freedom (SSF), the use of robots to accomplish as much of this maintenance as possible is required to allow the crew more time to perform productive, scientific work. Using robots exclusively in a teleoperation manner to accomplish this maintenance work, however, will only transfer the crew's maintenance efforts from extravehicular activity (EVA) to intravehicular activity (IVA). An assessment has been made of the net crew time required to perform maintenance using the SSF robots with the baseline automatic features as well as with collision-avoidance and ground-control capabilities added. It is recognized that teleoperation is being developed for use prior to complete assembly of the Space Station and that it will continue to be available throughout the operational lifetime of SSF.

Introduction

The three major maintenance requirements for the SSF robots are replacement of the robot-compatible ORUs, inspection of the passive structure, and support of EVA astronauts during maintenance operations. To accomplish these functions, the robots must also perform overhead tasks such as self-test and checkout, transportation to and from the worksite, and spare ORU retrieval and stowage.

It was reported in Appendix H4 that to operate the SSF robots exclusively in a teleoperational mode with the constant attention of two IVA crew members full time would require, typically, an end-to-end crew time commitment for a robot-compatible ORU changeout task of 26 to 30 man hours, and that a second ORU replacement would add about 4 man hours to this value range. The equivalent crew time commitment, both IVA and EVA, using the baseline EVA support equipment design for an EVA execution of two similar tasks is 36.5 man hours. Acknowledging the uncertainties in both these estimates, the conclusion still can be reached that overall, the baseline robot performance is comparable or better than EVA in terms of crew time required to perform compatible ORU changeout.

Determining that the use of robots does not require more crew time than an EVA is a significant finding of the External Maintenance Task Team study. At the time of the Cramer study, it was generally assumed that the robots would take a factor of three times longer to perform a task. Even at these newly determined rates, however, any combination of an EVA crew and robots would still require an excessive amount of crew time to meet the ORU replacement demand that has been determined through the SAIC study. A discussion of robot automation and the benefit of reducing crew time with the addition of collision avoidance and ground control follows.

Automating the Steps in the Robotics End-to-End Tasks

The end-to-end timeline analysis identified the steps in the robotic maintenance tasks to include the power up and checkout of the Mobile Transporter (MT), the Mobile Servicing Center (MSC), and either the Flight Telerobotic Servicer (FTS) or the Special Purpose Dexterous Manipulator (SPDM); various translations by the MT; MSC onloading and offloading of the FTS or SPDM; tool onloading or changeout by the FTS or SPDM; retrieval of the new ORU from the logistics carrier and installation of the failed ORU into the logistics carrier; positioning of the FTS or SPDM by the SSRMS at the worksite; and finally the removal of the failed ORU and the installation of the new ORU at the worksite. Values of a typical time to accomplish these steps were estimated based on specification data, simulation, or similarity with other steps.

These values are summarized in the accompanying table under the column headed Teleoperations Only. The values without parentheses assume that a robot-compatible ORU requires no more than one hour for replacement once the robots are in position at the worksite which is consistent with the EVA worksite time definition. The values with parentheses are for a "robot-difficult" ORU which is defined as requiring four hours of robot worksite time for replacement. The total time for one crew member to be fully committed to the entire robotic sequence is 11 to 19 hours. This range is intentionally broader than that of the Appendix H4 analysis to capture very simple as well as very difficult tasks. If the assumption is (properly) made that for teleoperations a second crew member is required, as is the current Shuttle RMS rule, the total crew time must be doubled to 22 to 38 man hours.

Since the end-to-end time exceeds what is usually considered a full day's work for most people, it should be noted that except for power consumption considerations, the robot can be interrupted at any time in the task for the convenience of its operators. This is in contrast to the EVA time which really is at a premium due to suiting-up considerations and the time limits on air supply.

The Baseline SSF Robot Capability column reflects in crew time commitment the benefit of the baseline autonomy of the self-test and checkout of the robots as well as the automatic translation of the MT. The assumption was made that for any step that is automatic, crew time commitment need be no more than 20% of the teleoperated value. This crew time is allowed for answering automatic caution and warning advisories and issuing reconfiguration or proceed commands. The reduction from the Teleoperations Only column is 47% for the compatible ORUs and 27% for the difficult ORUs.

If collision avoidance is added to the program, the effects are seen in the third column. Collision avoidance aides in all the positioning moves made by the robots and the removal and replacement of the compatible ORU. The difficult ORU is assumed to still require teleoperation. The reduction from the baseline is 60% and 29%, respectively.

Ground control relieves the crew of the management of the automatic steps in the timeline, thereby reducing the compatible ORU scenario to *zero* crew time required. The difficult

ORU scenario still requires 15 man hours total to perform the teleoperations at the worksite and the logistics carrier.

Development and Verification of Autonomous Robots

The key to the benefit of robot autonomy is the implementation of collision avoidance. This is leading-edge technology and carries with it a certain degree of technical risk. However, while the SSF robots are as complex as any space system that we have flown, the robots are no more complex and challenging than the Shuttle or Apollo systems that have been successfully developed and flown.

Implementation of collision avoidance requires the commitment of two on-board standard data processors to support the collision avoidance software during the time when the software is active. To initialize this software at the beginning of a robot task, geometric information describing the workspace of the robot needs to be provided to the on-board software. This geometric database can be resident on the ground, and the necessary local workspace description can be uplinked to the on-board processor. Such a "world model" of the SSF geometry could well serve to provide a consistent SSF model to the various simulators and trainers that are being developed. Currently, responsibility for such a database has not been established within the SSF Program.

Other Components of Robot Autonomy

In addition to collision avoidance, there are three other components to robot autonomy that are in development by the robot designers and must be fully verified prior to commitment to use of automatic control above the SSF design baseline.

These capabilities are machine vision, path planning, and fault tolerance. All are equally important, and all involve flight software design. Machine vision and fault tolerance also involve flight hardware design.

Machine Vision

Machine vision involves both the sensing and interpretation of workspace objects and their motion as well as the correlation of this sensed and interpreted information with previous knowledge both of the workspace and of objects that may appear in the workspace. Storage of this *a priori* information is referred to as "world modeling" and can be used for path planning of the robot motions. It can be thought of as that kind of knowledge a human uses to walk through a familiar, but darkened, room. This kind of information becomes stale if the workspace changes, and it is the function of the machine vision system to sense and identify the changes in the workspace and to provide accurate updates to the world model.

The hardware involved in machine vision includes the vision sensors which may be generalized to include television cameras, lasers, infrared, radio frequency, and other devices. Computational hardware is used to process the sensed data. Software is used to process the information further and to relate the interpretation of the objects in the workspace to the world model. Computational software and hardware are also used for programming and storing the world model.

Industrial machine vision is currently available for recognition and isolation of simple objects in trays and bins, but the level of robust machine vision required for the Space Station robots to function automatically is still in the research laboratories. The designers of the SPDM indicate that machine vision will be part of the SPDM at orbital delivery in 1996. The FTS designers are conversant regarding machine vision but do not carry it as a current FTS capability.

Path Planning

Path planning is the function of resolving the trajectories required by a robot to perform a task with the constraints of the workspace in which the task is to be done. Simply put, path planning is getting the robot and its payload from point A to point B in a timely fashion without colliding with anything.

Path planning is implemented in software and consists of algorithms that use models of both the workspace and the robot and payload (that are retrieved from the world model) and guidance laws for the generation of trajectories of motion of the robot joints and extremities. These candidate motions are compared with the geometries of the workspace to determine if any collisions will result if the trajectories are commanded. If a collision is indicated, the process is repeated with a change introduced in the candidate trajectories based on an optimization algorithm.

For simple workspace geometries and robots with few degrees of freedom, path planning can be straightforward and the algorithms will converge quickly. For the workspace geometries of the Space Station and the number of degrees of freedom of the SSF robots, the computational loading is significant. The redeeming feature, however, of path planning is that it can be run in a background mode of computation rather than in real time such as a control law.

The designers of the FTS and MSC are pursuing implementations of collision avoidance and path planning for their respective robots, but as in the case of machine vision, path planning is dependent upon the world model being implemented.

Fault Tolerance

Fault tolerance is the ability of a spacecraft system to accommodate normally expected failures of its components with no loss or at least with a graceful degradation of its functionality. The most impressive example of this kind of capability is the Shuttle flight control system, which is designed to accommodate multiple faults without compromising performance. This system can experience failures in its sensors, computers, and control actuators without any deviation occurring in the Shuttle flight path.

The Shuttle RMS has backup systems to assure that it will not compromise the safety of the vehicle or the crew, but the RMS is not a fault-tolerant system. As a first-generation space robot, the RMS has been and continues to be a fully successful and capable system.

The SSF robots, being permanently committed to space, however, must be designed for more robust performance under failed-component conditions.

Fault tolerance involves both hardware and software considerations, and the hardware is both computational and electromechanical. It is a major challenge for the SSF robots because there is no experience base in the industry nor has any theory been developed in the research centers. The designers of SSF robots are pursuing concepts that are more fault tolerant than the Shuttle RMS, but while these designs may eventually be shown to be adequate, at present, they are unproven.

Total Operator Time for One Typical Robot Task for Robot-Compatible (and Robot-Difficult) ORU Replacement (All Time in Hours)

	Teleoperations Only	Baseline SSF Robot Capability	Baseline With Collision Avoidance Added	Baseline With Collision Avoidance and Ground Control Added
Self Test, Checkout of Robots	4.5	0.9	0.9	0
Transport Robots, ORUs Tools	2	0.4	0.4	0
On/Off Load Robots, ORUs, Tools	3(5)	3(5)	0.6(3.8)	0(3.5)
Positioning Robots at Worksite	0.5(3.5)	0.5(3.5)	0.1(0.7)	0(0)
Remove and Replace ORU	1(4)	1(4)	0.2(4)	0(4)
Total Time for 1 Crew	11(19)	5.8(13.8)	2.2(9.8)	0(7.5)
Total Time for 2 Crew	22(38)	11.6(27.6)	4.4(19.6)	0(15)

Space Station Freedom Reconfiguration Options

Appendix I

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July 1990

Space Station Freedom Reconfiguration Options

Abstract

The objective of this appendix is to propose methods by which the "more costly" external maintenance demand can be reduced by the relocation of selected ORUs to within a pressurized volume. Moving ORUs "inside" always results in a lower maintenance demand due to the reduced overhead required by IVA relative to EVA or EVR and is conducive to a more favorable environment from a reliability viewpoint. This approach does raise significant issues however. These are

- Limited space is available within the existing pressurized volume
- Some systems are hazardous to the crew
- Some equipment must be left outside because of functionality

It is feasible, however, to consider the relocation of equipment by utilizing the Work Package 1 module as the basic architectual building block for the station in addition to building up compartments within modules or sub-modules to house systems currently located externally. This compartmentalization ensures the isolation and containment of hazards and allows systems to be maintained by either IVA or EVA. In the case of systems requiring exposure to space, an approach might be to have only radiating elements or sensors mounted externally, with the rest of the ORUs located inside.

Introduction

Space Station Freedom external maintenance data have been reviewed to determine the potential for reduction in EVA maintenance achievable by relocating ORUs to a pressurized intravehicular (IV) environment. This study is based on ground rules that additional pressurized module volume could be made available as required and that safety and/or technical issues would be independently assessed and are not factors in this report. Constraints on this study are that (1) items which inherently must have exposure to the extravehicular (EV) environment to perform their intended function are not candidates for IV-relocation and (2) that the current SSF structure would not be modified beyond possible addition of pressurized modules and relocation of equipment inboard of the alpha joint.

Statement of Problem

Review of the Fisher-Price database, MDSSC maintainability data (inputs to the EMTT), and preliminary SAIC reports revealed that the high contributor systems to SSF external maintenance are the Thermal Control System (TCS), Fluid Management System (FMS), Data Management System (DMS), and Communication and Tracking System (C&T). The study was limited primarily to consider relocation of these systems to the pressurized environment. The Guidance Navigation and Control system (GN&C) was also included in this study because its location and form make it a good candidate for relocation. All other highly significant ORUs, by the Pareto Principle, were also evaluated for IV-relocation. Other ORUs were considered for IV-relocation if identified as related to hardware which was selected as an IV-relocation candidate. The ORU selection as an IV-relocation candidate was made without regard to the ORU's potential for telerobotic application. External maintenance contribution and reduction potential were made on the basis of maintenance actions per year (including applicable K-factors) but did not consider worksite time (MTTR).

Approach

Fisher-Price database printouts were obtained from Ocean Systems Engineering for each of the subject systems and for the entire SSF with all reports printed in descending order of maintenance actions per year to provide visibility to the high drivers. Each ORU in each system report was evaluated to identify items which inherently must have exposure to the extravehicular (EV) environment to perform their intended function and to identify any ORUs that could not be relocated to the pressurized environment without violating the second constraint as stated above. The MDSSC data were also used to verify accuracy of the subject system ORU lists as tagged and sorted by the database outputs. Corrections were made as required to complete this study and discrepancies reported to Ocean Systems Engineering for revision.

Results and Discussion

The following items were totally excluded as candidates for IV-relocation at this time for the reasons described in the Introduction:

TCS Radiator Panels, W2/7.14.4.E

TCS Condenser/Subcooler Module, W2/7.14.4.A

TCS Line Heater Strip, W2/4.14.5.A

TCS Thermal Insulation Strip, W2/4.14.5.B

TCS TCS Module Support Structure, W2/7.14.4.B

C&T External TV Camera Assembly, W2/7.16.4.A

C&T TDRSS Parabolic Antenna, W2/7.16.7.B

Smaller C&T antenna ORUs were deemed candidates on the basis that a pressurizable radome or temporarily pressurizable "bay" could be provided. External cameras were excluded; however, articulated fiber-optic viewing systems similar to borescopes may be a possible alternative, providing remote viewing for short distances outside the modules. Cameras could be located within the modules and used whenever video signals were preferred over viewing directly into the scope. Because of the large number of cameras owned by various WPs/IPs and located near the module pattern, and the relatively high failure rate of the cameras and associated video systems, this approach could substantially reduce total equipment requirements as well as maintenance demand (e.g., one camera used at any of several viewing scopes). Further study of this concept is recommended. All other TCS and C&T ORUs were selected as IV-relocation candidates.

All GN&C ORUs were considered suitable candidates for IV-relocation with proper provisions for star tracker viewing and CMG load reaction.

The DMS ORU list failed to printout the following ORUs, presumably due to non-matching system identifier tags:

MDM/MS (Quantity = 35), believed associated with TCS

MDM/SC (Quantity = 15), believed associated with PROP

MDM/EDP (Quantity = 2), believed associated with MT

Of the above MDMs, only the 35 associated with TCS were considered suitable as IV-relocation candidates. Of these 35, it is possible that some will be required to be located near the radiators. This study did not consider it feasible to remotely locate the propulsion and mobile transporter MDMs. The study did assume that 30% of the Payload Interfaces (APAEs) could be IV-relocated, based on assumed short distances to some of the payloads. This assumption was provided by MDSSC-HB Maintainability Engineering. All other DMS ORUs were selected as candidates for IV-relocation.

The FMS ORU list, as printed out from the Fisher-Price database, was missing many ORUs. The original MDSSC inputs to the EMTT were utilized as the primary information source. All pallet-mounted FMS equipment, including the INS, IWFS (RWG and MWG), and Fluid Control Network ORUs (WBS 2.20) were considered as IV-relocation candidates. All of these ORUs (23 types) were identified in the printout of the entire SSP database along with applicable maintenance action per year data. Ocean Systems Engineering was notified of this problem, and corrections were made to the system identifier in the Fisher-Price database for future efforts. An additional 12 ORU types were identified as FMS utility tray lines and equipment (WBS 2.24.4) and also reported to Ocean Systems Engineering. For the purposes of this study, it was assumed that a 30% reduction in FMS lines/equipment (and hence, maintenance actions) would result from other associated IV-relocations. This assumption was provided by the FMS Maintainability Engineer.

The entire SSF "heavy-hitters" list was reviewed to identify additional candidates for IV relocation. Most of the remaining valid entries on the list were either Solar Power Module (SPM) equipment, SPAR equipment, or other items which inherently must have exposure to the EV environment to perform their intended function. External cameras appear in multiple applications in the "heavy-hitter" list; therefore, camera alternatives should be explored. Relocation of the WP-4 Integrated Equipment Assembly (IEA) was beyond the scope of this study; however, several EPS ORUs located inboard of the alpha joint were considered for IV-relocation. It was found that at least some of the DDCUs and RPCs could be considered candidates, particularly since some of the equipment being served were candidates, and the DDCUs and RPCs are significant contributors to the SSF maintenance workload. For the purposes of this study, it was assumed that 80% of these Electrical Power System (EPS) ORUs could be relocated to the pressurized environment.

The list of all IV-relocation candidates is provided as an attachment.

Results of this study are as follows:

System	Potential EVA Reduction (MA/Y)
Thermal Control System	30.3
Data Management System	25.1
Communication and Tracking	16.6
Guidance Navigation and Control	4.3
Fluid Management System	12.0
Electrical Power System	19.6
Total IV-Relocation Potential	107.9

Recommendations

The EMTT recommends the Program weigh the merits of this approach. Of particular interest is the recommendation concerning the use of fiber-optic technology in place of CCTVs. The savings potential relative to external maintenance requirements is about 30% of the current demand.

Concluding Remarks

It should be noted that this is the upper limit of potential for EVA reduction by IV-relocation. Detailed technical and/or safety issues have not been evaluated as a part of this study. Impact of reduced EVA or robotic activity will reduce demand for maintenance of these systems; however, this effect has not been evaluated as a part of this study. The ORUs which were not on the "heavy-hitters" list may also be considered for relocation; however, the EVA reduction associated with these ORUs is expected to be minimal since these items, by definition, do not contribute significantly to the totals. Future updates to the Fisher-Price database, particularly with respect to non-operating failure rates and wear-out failures could provide additional candidates and significant additional potential for EVA reduction.

Acknowledgments

This appendix was developed by the McDonnell Douglas Space Systems Company - Space Station Division (MDSSC-SSD). The principal author was Dave Cheuvront, MDSSC-SSD, Houston, Texas.

Appendix I

Attachment 1
Candidate ORUs for IV Relocation

Data Management System ORUs

ORU NAME	QUANTITY
Drive Electronics	2
Bus Network Interface Unit	5
Ring Concentrator	10
MDM-MS	35
Payload Interface (APAE)	20 (30% are candidates)

Communications and Tracking System ORUs

ORU NAME	QUANTITY
SSS Transmitter-Receiver Type 3	8
SSS Transmitter-Receiver Type 2	6
External Video Switch	2
SSS Parabolic Antenna control	4
Ku-Band TDRSS Trans-receiver	4
Ku-Band TDRSS Antenna Control	4
ACS Transmit-Receiver Amplifier	2
TDRSS Parabolic Antenna	2
SSS Parabolic Antenna Assembly	4
S-Band TDRSS Antenna Assembly	3
GPS Low Noise Amplifier	3
GPS Antenna	3
SSSOmni Antenna	6
UHF Omni Antenna	4

Guidance, Navigation, and Control System ORUs

ORU NAME	QUANTITY
Alpha/Radiator Joint Electronics	8
CMG Electrons Assembly	12
Ineritial Sensor Assembly	3
Control Moment Gyro Assembly	6
Star Tracker	3

Fluid Management Systems ORUs

ORU NAME	QUANTITY
N2 SC Heater Assembly	2
N2 Vent/Safety Assembly	2
N2 Pressure Sensor Assembly	2
Interconnecting Valve Assembly	1
Pressure Bleed Assembly	2
Waste Gas Dump Assembly	1
Tank Inlet Control Assembly	2
Tank Discharge Control Assembly	2
Instrumentation Assembly	2
RWG Inlet Pressure Sensor Assembly	1
RWG Intermediate Pressure Sensor Assembly	2
RWG Compressor Assembly	2
RWG Dryer Assembly	2
RWG Discharge Filter Assembly	1
MWG Inlet Pressure Sensor	1
MWG Vent/Safety Assembly	1
MWG Intermediate Pressure Sensor Assembly	2
MWG Compressor Assembly	2
MWG Dryer Assembly	2
MWG Discharge Filter Assembly	1

30% of the following UDS located components are candidates

Interconnect Lines	227
Umbilical Flex Hose	30
H2O Interconnect Line Heater	4
Temperature Sensor	12
Hose	60
Fittings	243
Umbilical Flex Hose	24
Fluid Utility Junction Asembly	2
Tubing and Fitting Set	26
Fluid Control Cable Assembly	20

Thermal Control System ORUs

Filter Assembly	8
Pump Assembly	8
N2 Pressure Regulator	9
Heat Exchanger Units	18
Pressure Regulator Ammonia	8
Accumulator	4
Isolation Valve	12
Dump Tank	1
Supply Tank	1
Recirculating Control Valve	8
External Module Coldplates	8

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